CONFIDENTIAL

SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 18, NDRC

VOLUME 1

WAR METALLURGY

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 18
CLYDE WILLIAMS, CHIEF

WASHINGTON, D. C., 1946

[redacted]

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance

Division B—Bombs, Fuels, Gases, & Chemical Problems

Division C—Communication and Transportation

Division D—Detection, Controls, and Instruments

Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC; account must be taken of the monographs and available reports published elsewhere.

The field of wartime research of Division 18 was metallurgy. The objective of the Division, under the leadership of Clyde Williams, was to aid in improving metallurgical processes and metallic materials of war and in promoting the conservation of scarce and strategic materials.

The Division was unique among the NDRC groups in that it carried out its technical functions through the War Metallurgy Committee, a coordinating unit of thirty outstanding metallurgists and engineers created by the National Academy of Sciences and the National Research Council.

The metallurgical research program was not concerned with the development of any specific military equipment or finished product, but rather with materials and processes. Yet, though the program had no startling device to advertise it, its results were literally built into planes and rockets, ships and guns and tanks.

The Division's Summary Technical Report has been prepared under the direction of, and has been authorized for publication by, the Division Chief. To him, to the divisional staff, to the members and staff of the War Metallurgy Committee, and to workers in the many contracting laboratories go our appreciation and thanks.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

THE FOLLOWING summary technical report of the work of the War Metallurgy Division (Division 18) of the National Defense Research Committee [NDRC] gives a complete picture of the aims and accomplishments of the Division's research program described in such detail as seems adequate. To this presentation the Division Chief has nothing to add by way of technical comment or emphasis.

I do wish, however, to make acknowledgment to the editor, David C. Minton, Jr., for his painstaking work in assembling, or himself writing, the several sections of the report and in editing and coordinating the entire report. He already has made acknowledgments in his preface to those who prepared the original manuscripts for the several sections and who otherwise assisted in the work. In all these acknowledgments I wish to join.

After the specific acknowledgments in this report have been made, there still remains a very great indebtedness on the part of the War Metallurgy Division to many other agencies, organizations, and individuals.

The work of Division 18 was to undertake research to improve metallurgical processes, to improve metallic materials of construction, and to promote conservation and substitution of scarce or strategic metallic materials, all as applied to the production of instrumentalities of war. Recognition of the desirability of the coordination of defense and war research in metallurgy with industry and with research agencies and technical societies prompted the Office of Scientific Research and Development [OSRD] and NDRC in 1941 to enlist the assistance of the National Academy of Sciences and the National Research Council as channels through which NDRC metallurgical research might be accomplished.

The Division's thanks are tendered to OSRD and NDRC for providing and supporting this channel of operation and to the National Academy of Sciences and the National Research Council for organizing and operating within their framework the War Metallurgy Committee to make effective the desired cooperative effort in metallurgical research. This cooperative effort was made possible by the members of the War Metallurgy Committee and several hundred industrial and university metallurgists, engineers, and research workers who served on the various project advisory committees, their time and technical advice being contributed by their employers without charge.

In addition to contributing advice, industry gave without restrictions its accumulated knowledge, results of research, and helpful comments and criticism. This invaluable information was used by the War Metallurgy Committee in appraising problems and in planning and directing the research projects of the Division's program. The members of the War Metallurgy Committee and of the many project advisory committees, who together represented all phases of the metallurgical industry, were kept informed of the progress of the investigations so that the results could be utilized immediately in their research work and in war production. This free interchange of information and ideas was particularly desirable in the work of the War Metallurgy Committee because its greatest value lay in obtaining and disseminating industrial "know-how" so that instrumentalities of war could be made from materials available, often using substitute materials which required special methods of processing. This is in contrast with much of the other work of NDRC which was concerned with the development of specific military devices or finished products. Thus, the Division was able to provide information not only for the use of the Armed Services and their contractors, but also for the use of other Divisions of NDRC.

The accomplishments of the Division, which were made possible by the activities of the War Metallurgy Committee, provide an outstanding example of the results of cooperation between industry and governmental agencies in time of emergency. Thus, the Division's activities throughout were truly cooperative and coordinating. The Division is fully as proud of its accomplishments in these aspects of its work as in any technical accomplishments, and by the same token it is sincerely grateful to all who helped in this cooperation.

The Division is indebted and grateful also to the Armed Services, not simply for the formally designated liaison, but for the sincere and active interest and participation in the Division's program by all echelons of the Services' research and development organizations.

CLYDE WILLIAMS
Chief, Division 18

PREFACE

THIS REPORT summarizes the metallurgy work on instrumentalities of warfare carried out under the direction of the War Metallurgy Division (Division 18) of the National Defense Research Committee [NDRC].

The first purpose of this report is to serve as a guide to help the future student of the original reports to select those dealing with the subject in which he is interested. Often a number of projects relate to the same general topic.

A second object is to give a broad view of the results obtained and of their engineering meaning, which may sometimes in itself be sufficient for the reader's purpose, but more often may guide him to the particular report that he will want to consult for details.

In this connection, an attempt has been made to phrase the report so that the meaning of the results will be clear to a reader with general engineering background, even though he is not a metallurgical expert. However, some of the projects are so technical and specialized that a reader must be something of an expert in the particular field to grasp even a not-too-technical report. Reports on such topics probably will be referred to only by experts, so it has not been considered necessary to define technical terms or to discuss the elementary fundamentals involved.

The projects discussed in this report were given a place on the war research program because experts believed that information on them could be used to further the war effort. They were carried only as far as it appeared that the information would be useful in World War II, although their further prosecution in more leisurely fashion might be of value in commercial problems or as a measure of preparedness against a future war.

However, there are some projects in which matters were brought to such a stage that continuation and expansion of the research programs obviously should go on without interruption after demobilization of NDRC. In these cases, further work by or for the Armed Services usually has been arranged, and, since the situation is continually changing, it appears undesirable to go into detail relative to such projects in this report.

An appraisal of the direct and indirect influence of the work in some quantitative terms would be interesting, but the present writers, unable to make such an appraisal, have not attempted it. Such an appraisal could be made only by the Armed Services. It would be a very difficult task, since many tributaries fed the main stream of advancing knowledge of the production and the processing of metals and alloys. Service and civilian engineering and research, the civilian work directly sponsored by the Armed Services, work of the other NDRC divisions and of the War Production Board [WPB], as well as studies carried on under still other auspices all blended together; and it would be virtually impossible to determine which drop of water in the main stream came from which tributary. That there already was considerable water in the stream is indicated by the fact that the bibliography[1] on armor, armor-piercing projectiles, and the welding of armor prepared by Watertown Arsenal contained 1,197 entries on armor, 457 on armor-piercing projectiles, and 121 on welding. This bibliography covered work only through 1942.

In accordance with the instructions issued for the preparation of this report, no attempt has been made to allocate credit to the individuals who contributed to the work done. Rosters of the supervisory and advisory personnel appear in the back of the volume. Although the institutions where the research was carried out are mentioned in the text of this report, the bibliography must be consulted for the names of the authors of the reports who were, in most instances, the principal investigators. The names of those who supervised the work in behalf of the government and those who served on the many project advisory committees are given in the distribution lists of the various reports cited in the bibliography of this report.

This summary technical report is based in part on an editorial summary of most of the reports of Division 18 that was written by Dr. H. W. Gillett, a member of Division 18 and of the War Metallurgy Committee. Indeed, much of Dr. Gillett's summary has been incorporated verbatim into this summary technical report by those who prepared the several chapters. Chapter 2, "Armor," was prepared by Dr. C. H. Lorig of Battelle Memorial Institute and Supervisor of Armor Metallurgy Research, War Metallurgy Committee. Most of Chapter 3, "Guns and Gun Steels," was prepared by Dr. Cyril Wells, an investigator on the NDRC gun steel projects at Carnegie Institute of Technology. The armor and ordnance section of Chapter 6, "Welding," was prepared by Dr. A. Muller; the section on ship welding and

welded steel ships of the same chapter was prepared by Dr. Finn Jonassen. Both of these men are Assistant Supervisors of Welding Research, War Metallurgy Committee. Chapter 5, "Metals for High Temperature Research," was prepared by Mr. Howard C. Cross of Battelle Memorial Institute and Supervisor of High Temperature Metals Research, War Metallurgy Committee. Chapter 1, "Aircraft Materials"; Chaper 4, "Ammunition"; Chapter 7, "Foundry Materials and Processes"; Chapter 8, "Enemy Matériel"; and Chapter 9, "Miscellaneous Materials for War," were prepared by Mr. David C. Minton, Jr., Senior Technical Aide, Division 18, and Research Supervisor, War Metallury Committee. The Summary was prepared by Mr. V. H. Schnee of Battelle Memorial Institute and Chairman, Products Research Division, War Metallurgy Committee, under whose charge the technical administration of the work of Division 18 was conducted.

In addition to those named above, the editor acknowledges with thanks the assistance of Mr. Louis Jordan, Technical Aide to the Chief, Division 18, and Executive Secretary, War Metallurgy Committee; and Mrs. S. L. Kruegel, Technical Aide of Division 18 as well as of the War Metallurgy Committee.

In the editing and compiling of this report, considerable license was taken with the material prepared by those named above in order to make the report as uniform as possible.

David C. Minton, Jr.
Editor

This volume, like the seventy others of the Summary Technical Report of NDRC, has been written, edited, and printed under great pressure. Inevitably there are errors which have slipped past Division readers and proofreaders. There may be errors of fact not known at time of printing. The author has not been able to follow through his writing to the final page proof.

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A master errata sheet will be compiled from these reports and sent to recipients of the volume. Your help will make this book more useful to other readers and will be of great value in preparing any revisions.

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INTRODUCTION

ORGANIZATION OF DIVISION 18

The personnel of the War Metallurgy Division (Division 18) comprised a chief, three technical aides, and four members. These are listed on page 153 of this report.

Division 18 carried on its functions through the War Metallurgy Committee of the National Academy of Sciences and National Research Council, which was an outgrowth of earlier committees of the National Academy of Sciences and National Research Council.

The War Metallurgy Committee assumed the continuing functions of several smaller advisory committees; namely, the Technologic Committee on Manganese, which was appointed by the National Academy of Sciences in July 1940 at the request of the Advisory Commission to the Council for National Defense (later succeeded by the Office of Production Management which in turn was succeeded by the War Production Board); the Advisory Committee on Tin Reclamation, which was appointed in September 1940 at the request of the Advisory Commission; the Advisory Committee on Metals and Minerals, which was formed in January 1941 at the request of the Office of Production Management; and the Metallurgical Advisory Committee and the Welding Advisory Committee, which were formed as a result of a request of the Office of Scientific Research and Development in July 1941.

It soon became apparent that the last two committees could be combined to advantage, since many of the technical problems involved in the development of new weapons involved not only metallurgical improvements but also definite advances in welding techniques and materials. The Metallurgical Advisory Committee which began to function in October 1941 undertook to develop the necessary welding research programs as well as a metallurgical research program. In March 1942, the Metallurgical Advisory Committee was asked by the War Production Board to organize and supervise research in the field of production of metals and minerals. In May 1942, it began the organization of a comprehensive research program financed largely by the War Production Board.

In order to operate these various activities efficiently, in May 1942 the War Metallurgy Committee was organized. The relationship between the War Metallurgy Committee and the various government agencies which it served is shown diagrammatically on page 154.

The committee proper was made up of 30 of the nation's outstanding scientists, metallurgists, and engineers including 26 civilians, 3 Army officers, and 1 Navy officer. The committee laid down broad principles and acted as an overall advisory committee. Although it met in a body only once each year, smaller groups of the members met from time to time to discuss specific problems in their fields and many decisions were arrived at through balloting by mail. A listing of the members of the War Metallurgy Committee is given on page 155.

The administration of the committee was under a chairman who was responsible for overall operations, a vice-chairman who was responsible for advisory reports and technical surveys, and an executive secretary who was responsible for administrative matters.

The activities of the committee were carried on by four major divisions, each of which was in charge of a chairman whose duties were similar to those of a section chief in the usual NDRC division:

1. The Advisory Division, which prepared reports for, and at the request of, the War Production Board primarily, but also other government agencies and the Army and Navy.

2. The Processes Research Division, which was responsible for the organization and supervision of research projects, largely for the War Production Board, dealing with the development of new or improved processes for the production of metallic or mineral products and for the conservation and substitution of materials.

3. The Products Research Division, which was responsible for the organization and supervision of projects dealing with development or application of new or improved products and fabrication processes for instrumentalities of warfare. Most of these projects were conducted for the National Defense Research Committee [NDRC] of the Office of Scientific Research and Development [OSRD].

4. The Research Information Division, which had charge of the collection and dissemination of classified or unpublished information in the field of metals and minerals as a service to the research divisions and to the contractors under their supervision.

In the work of the Advisory Division, emphasis was placed on bringing to bear on every question or problem submitted by government agencies the best talent and all of the scientific and practical information available to the committee through the large number of specialists serving on its subcommittees. The work of the Advisory Division was performed by the Advisory Committee on Metals and Minerals, one of the forerunners of the War Metallurgy Committee. This Advisory Committee was comprised of 70 specialists who were selected because of their abilities, not their positions. The basis for the selection of this committee, as with subsequent committees, was experience, judgment, and leadership in the particular field of activity. The Advisory Committee on Metals and Minerals comprised five groups:

1. Metals conservation and substitution group.
2. Ferrous minerals and ferro-alloys group.
3. Tin smelting and reclamation group.
4. Nonmetallic minerals group.
5. Alumina group.

The Advisory Division and its predecessors have prepared a total of 200 reports touching on the fields of practically all the important metals and involving studies of new methods of production, recommendations for the substitution of one metal for another and of other materials for metals, and suggestions as to how scarce metals could be conserved. Most of these reports were prepared at the request of the War Production Board, although some were prepared at the request of various branches of the Armed Services, NDRC, the Defense Plant Corporation, and the National Advisory Committee for Aeronautics [NACA]. Many included confidential company information which was made available to the committee by industry for the use of the various government agencies in making decisions concerning war production.

In the work of the research divisions, emphasis was placed on close supervision of each project by a competent research director who was provided with the constant advice of committees of experts in the particular field concerned. In carrying out the research program, 32 research supervisors were employed. Each of these supervisors had charge of one or more projects in his field and visited them from time to time to consult with and advise the investigator on his research program. The research supervisor also coordinated the work of the related projects in his field and consulted with representatives of the government agencies interested in the work. The duties of a research supervisor of the War Metallurgy Committee were similar to those of a technical aide in the usual NDRC divisional organization. Each project or group of related projects had a project committee which assisted the supervisor in outlining his program and establishing technical policy. These committees consisted of experts in the particular fields concerned as well as liaison representatives of the government agencies interested in the problem under study. In this manner, advice from those experienced in the field as well as from those who needed the information was available to the supervisor and through him to the project investigator. Meetings of the project committees were held at frequent intervals to review the results of the work done when phases of the program were completed or when recommendations as to the continuation of the project or changes in the program were necessary.

Each research supervisor and his project committees were kept informed of the progress of the work on each project under his supervision through informal monthly reports and formal progress reports prepared by the investigator on each project.

The Office of the Executive Secretary of the War Metallurgy Committee not only handled the collection, duplication, and distribution of reports, but also served as a headquarters for the committee staff and records, maintained liaison with government agencies and the Armed Services, and performed numerous administrative functions. Among these were processing deferments for the contractors' personnel; obtaining the necessary priorities for the purchase of research supplies and equipment; arranging for the security clearances of staff and contractors' personnel; arranging for clearances for the staff members and contractors' personnel to visit government laboratories, arsenals, proving grounds, etc., as well as other laboratories under government contracts; and keeping the staff and contractors advised of new regulations affecting their activities.

The Research Information Division collected information from domestic and allied government sources, classified it, and distributed it to the various supervisors and investigators concerned so that they

could benefit by the efforts of other investigators working in their fields. This information included not only that of our government and allied government laboratories but also available information concerning the activities of the enemy in the field of metallurgy. The Research Information Division also maintained a staff of librarians who abstracted and indexed the research reports issued so that the information was correlated and made more readily usable by the government agencies, Armed Services, and their contractors engaged in war production.[2,3]

A roster of the staff of the War Metallurgy Committee is given on pages 156-157.

SOURCES OF RESEARCH PROBLEMS

The research problems upon which the War Metallurgy Committee program was based emanated from several sources. These are shown diagrammatically on page 154. Many projects were undertaken as the result of recommendations made by civilian *ad hoc* committees appointed by NDRC or the War Metallurgy Committee. Some projects were undertaken because the members or staff of the War Metallurgy Committee were familiar with problems of industry; others were studied at the request of the War Production Board. To avoid overlooking such problems vital to the war effort, the War Metallurgy Committee employed recognized experts to make surveys of the available information in their fields so that the gaps or research needs could be ascertained and research speedily initiated.

Naturally, these gaps were in widely varied fields, the only necessary feature of similarity being that the problems all concerned metallurgy or metallurgical engineering in the war effort. In rare cases, projects were undertaken that, on the basis of available information, had but a slight chance of success. This was because the possibilities had not been exhausted and even a slight chance of success was worth taking. These were, in the main, unsuccessful and were terminated as soon as convincing evidence had been accumulated that, with present-day knowledge and facilities, hope of securing information in time for application in World War II was still vanishingly small. Many of the projects were on topics already under investigation by the Armed Services or already in the minds of their representatives as deserving of study when opportunity and funds permitted. When the Armed Services were unable to continue their work, a program was planned either to carry it on from whatever point the Services had reached or to dovetail it into their continuing work. These studies were requested of NDRC through the War Department Liaison Officer for NDRC, Headquarters, Army Service Forces, or the Coordinator of Research and Development (later the Office of Research and Invention) of the Executive Office of the Secretary of the Navy. A listing of the Army and Navy projects assigned to Division 18 with the Division 18 projects pertaining to each is given in Appendix E.

Almost all the projects established on problems relating to instrumentalities of war and originating outside of the Armed Services were subsequently adopted by the interested branches of the Services and appropriate liaison established so that they could be conducted with maximum benefit to the Services.

ESTABLISHMENT OF RESEARCH PROJECTS

After appraisal of a problem, a research program was formulated, and a contractor selected whose facilities, personnel, and experience might best be utilized to attack the problem and to conduct the program speedily and efficiently. Proposals for the financing of these projects were reviewed and approved by the members of Division 18 prior to presentation to NDRC. As the War Metallurgy Committee also supervised research on production, conservation and substitution, and process metallurgy problems for the War Production Board, proposals for financing research on such problems were submitted to the Office of Production Research and Development [OPRD] of the WPB. (See page 154.)

The types of projects established included research projects, correlation projects, and survey projects. The research projects involved laboratory investigations and were financed by OSRD or OPRD under contracts between those agencies and the research laboratories. Correlation projects were investigations which were financed by industrial concerns but carried out under the general supervision of the War Metallurgy Committee, the results of the investigations being submitted by the War Metallurgy Committee to NDRC and distributed to the Armed Services and their contractors in the form of NDRC reports. Survey projects were field investigations carried out by engineers or committees designated by

the War Metallurgy Committee to collect and correlate the available information on a given subject so that the research needs could be determined. In many cases the information made available by industry was sufficient for government purposes and obviated the necessity for establishing research projects.

All contractual and fiscal relationships with the OSRD contractors under the jurisdiction of Division 18 were the responsibility of and were conducted by the Division staff even though technical supervision and administrative duties were carried out by the War Metallurgy Committee.

THE RESEARCH PROGRAM OF DIVISION 18

The research program of Division 18 included the study of metallurgical problems involved in the production of materials and instrumentalities of war. The specific objectives of the work were to improve the qualities and properties of metals and alloys used in military vehicles, equipment, weapons, and ammunition; to improve the methods of producing and fabricating such metals and products; and to increase the production of such military products by the development of substitute materials having acceptable properties. Unlike most of the other NDRC divisions, Division 18 was never concerned with the development of a specific military device or of a finished product. The Division 18 work itself comprised fundamental research complemented by applied research designed to reduce the technical findings to the practical production of military goods by industry.

The technical program of Division 18 as carried out under the supervision of the War Metallurgy Committee embraced 91 contract research projects, 11 correlation projects financed by industry, and 21 survey projects, or a total of 123 investigations on a wide variety of subjects. A listing of the Division 18 contract and correlation projects is given on pages 162-165. This listing also gives the contractual information for each contract, the name, address, and technical representative of each contractor, and the title of each project. A listing of the War Metallurgy Committee survey projects carried out for NDRC is given on page 166.

For convenience, the Division 18 program has been subdivided by materials or processes in this summary technical report in the same manner as in the semiannual Division 18 memoranda reports to the Office of the Chairman, NDRC. These broad subdivisions, which are also chapters of this report, are as follows:

Chapter 1. Aircraft Materials.
Chapter 2. Armor.
Chapter 3. Guns and Gun Steels.
Chapter 4. Ammunition.
Chapter 5. Metals for High-Temperature Service.
Chapter 6. Welding.
Chapter 7. Foundry Materials and Processes.
Chapter 8. Enemy Matériel.
Chapter 9. Miscellaneous Materials for War.

The attention of the reader is called to a comprehensive index[2] of all the 661 Division 18 reports. As stated before, the War Metallurgy Committee also supervised research on production, conservation and substitution, and process metallurgy problems for the Office of Production Research and Development. These projects are not discussed in this report, but, in many instances, particularly in investigations of aircraft materials and welding, the OPRD work complements that of NDRC. An index[3] of the 163 research reports and 200 advisory reports submitted by the War Metallurgy Committee to OPRD is given in the bibliography and will assist in giving the reader a better understanding of the overall picture of the metallurgical research carried out by NDRC and OPRD during World War II.

SUMMARY

Each of the nine parts of the Division 18 research program consisted of a group of related projects concerned with metallurgical problems pertinent to the production of materials for instrumentalities of war. The program comprised fundamental research complemented by applied research to reduce the technical findings to the practical production of war matériel by industry. The specific objectives of the work were to improve the qualities and properties of metals used in military products, to improve the methods of producing and fabricating such metals and products, and to increase the production of such military products by the development of substitute materials having acceptable properties. A brief résumé of the accomplishments of each of the nine parts of the Division 18 research program is given in the following summary, and more detailed treatment is given in the body of this report.

AIRCRAFT MATERIALS

This part of the research program was concerned primarily with the study of the light alloys, aluminum and magnesium. The mass production of aircraft undertaken for the first time early in the war effort introduced a host of new problems. The transition from hand forming and cut-and-try methods of fabrication to production practice called for the immediate collection and dissemination of a mass of fundamental data on the forming properties of the aluminum alloys. An extensive survey of industrial fabrication operations was undertaken, and a correlated digest of the information was distributed widely through the aircraft industry by the Production Aids Unit, Bureau of Aeronautics, Navy Department. Based on this survey, three research projects were established to secure needed additional information on the forming characteristics of aluminum alloys. These projects were extended later to study the properties and forming characteristics of the stronger aluminum alloys which became available during the war.

Surveys to collect and disseminate information on the effects of impurities in aluminum alloys, on the fatigue and impact characteristics of the heat-treated alloys, and on the high-temperature properties of both magnesium and aluminum alloys were conducted. A preliminary study of the possibilities of casting or forging high beryllium-aluminum alloys for possible use in lightweight engine parts indicated great commercial difficulties and consequently was not carried to completion.

Early in the war, there was considerable doubt that sufficient supplies of aluminum could be developed in time to satisfy the leaping requirements of the aircraft production program. New and greatly increased production facilities for magnesium were authorized and ample supplies of this virtually new metal seemed assured. It appeared necessary to secure as rapidly as possible the engineering data which would permit the aircraft designers to evaluate or to use magnesium alloys in the construction of airframes. Five research projects were established. Two of these were planned to study the mechanical properties and the fatigue characteristics of the then available magnesium alloys. Two were concerned with studies of forming characteristics and another with the stress-corrosion of magnesium alloy sheet. Alloys with a high level of property values were not developed, but new techniques in casting and heat treatment resulted in increasing materially the resistance to stress-corrosion of certain of the commercial alloys. Work on the development of new magnesium alloys is being continued both by the Bureau of Aeronautics, Navy Department, and the Army Air Forces.

Research on the development of carbon steel aircraft control cables, with adequate corrosion resistance, to replace stainless steel cables resulted in cable with improved performance characteristics and provided data for use in the revision of specifications covering aircraft control cables. A project on mechanical surface treatment made possible a substantial improvement in performance of a number of engine and ordnance parts. In many instances, this treatment, shot peening, obviated the necessity for redesigning parts which had been put into production but were suffering premature failures in service.

In order to assist in the standardization of test methods used in the procurement of aircraft materials, a comprehensive survey was made of the test

methods of the Materials Laboratory, Air Technical Service Command [ATSC], Wright Field. Another survey was carried out on the fatigue of aircraft structures and materials so that the research needs in the field could be ascertained.

ARMOR

Ten projects on the metallurgy of armor and armor steels were conducted. The principal project was a broad study of the fundamental metallurgical problems encountered in the production and heat treatment of armor plate. Starting with problems of conservation and substitution brought about by the critical shortages in alloying elements at the beginning of World War II, the work included studies of the effect of gas in armor steel, the correlation of metallographic structure and hardness of armor plate, the improvement of the ballistic properties of low-alloy armor plate, the effects of various elements on the quench-cracking susceptibility of cast armor, and the development of methods for the production of face-hardened armor plate.

Supplementary projects were conducted to make more detailed investigations of the more important problems, notably the use of boron as a hardening element, the use of flame hardening, and the development of nonalloy armor plate.

Other investigations were concerned with the development of a nonballistic test and a direct explosion test for armor quality. The nonballistic test was capable of predicting failure by spalling but was not reliable for predicting cracking. The direct explosion test showed considerable promise for use as a screening test prior to ballistic testing and as a method of eliminating much of the human equation in evaluating ballistic results.

These projects were conducted with the close cooperation of Watertown Arsenal and the subcommittees on Cast and Rolled Armor, Ferrous Metallurgical Advisory Board, Army Ordinance Department. They resulted in improvements in practice for cast armor, improvements in face-hardened armor, and a better understanding of the role of composition, gas content, and microstructure on the ballistic properties of armor plate.

Another project of interest to the Bureau of Ordnance, Navy Department, and the Army Air Force was an investigation of nonmagnetic or magnetically stable armor plate for aircraft. This included determination of the ballistic properties of a number of nonmagnetic steel compositions made with various heat treatments.

GUNS AND GUN STEELS

Eight coordinated projects relating to gun tubes and gun steels were conducted in close cooperation with Watertown Arsenal, Watervliet Arsenal, and the Research Group of the Subcommittee on Gun Forgings, Ferrous Metallurgical Advisory Board, Army Ordnance Department.

In this program, two projects were concerned with the quality of steel used in the manufacture of wrought gun tubes. Both laboratory and statistical studies were made, and as a result of these studies data were supplied for the revision of the specifications for wrought gun tubes, making it possible to secure adequate quality of gun steel as well as the finished gun. Testing procedures were also simplified, thus making substantial savings in time and money with an overall increase in the number of satisfactory guns produced. Under a project on the improvement of gun steel ingot practice, a study was made of the relation between ingot practice and bore defects and of the effects of bore defects on the performance of 40-mm and 75-mm seamless gun tubes. A classification of bore defects based on these studies was prepared to assist in the inspection of gun tubes. Under a project on the prevention of cracking in gun tubes, a test for cracking susceptibility was developed, the causes of quench cracking were determined, and remedies were outlined for reducing quench-crack losses. Certain of these projects are being continued under contract with the Ordnance Department.

A project on the control of basic open-hearth melting practice for the manufacture of wrought gun tubes correlated the numerous manufacturing variables with the quality and physical properties of gun tubes. Two other projects on the processing of wrought gun tubes dealt with the heat treatment of gun steels. One of these projects developed a test method for determining the correct tempering temperatures for fully hardened and tempered gun tubes. This method was adopted by manufacturers of gun tubes and resulted in the development of improved heat treating practices, materially decreasing rejections with a corresponding increase in finished gun tubes.

At the close of World War II, a project was under

way to develop new gun steels with greatly improved properties for use in connection with new designs developed by the Army Ordnance Department.

AMMUNITION

At the request of the Office of the Chief of Ordnance, investigations were carried out on materials for three components of ammunition: armor-piercing shot, cartridge cases, and driving bands.

The project on armor-piercing shot was concerned with studies of nonalloy steels treated with special addition agents and resulted in the development of armor-piercing shot with superior ballistic properties.

Three investigations relating to the stress-corrosion cracking of cartridge brass were conducted with the close cooperation of Frankford Arsenal where work of a similar nature was being carried on. One project was concerned with the prevention of stress-corrosion by surface protection or treatment and resulted in the development of new protective coatings, one of which demonstrated the efficacy of thin electroplated zinc coatings and the electrochemical protection afforded to scratched areas. Under a project relating to the detection and elimination of internal stresses contributing to stress-corrosion, methods of measuring the stresses introduced in the cartridge case manufacturing processes by X rays were developed and applied to lots of sample cases from Frankford Arsenal to permit better production control. A study of the effect of volume changes associated with phase changes in cartridge brass revealed that the effect was negligible and that proper annealing eliminated the laminated structure caused by the presence of the zinc-rich phase.

METALS FOR HIGH-TEMPERATURE SERVICE

Work in this field was instituted at the request of the Navy Department to develop new alloys and to establish design data for the commercial alloys available for high-temperature service in the gas turbine used for ship propulsion. In order to expedite the investigation, the facilities of 12 laboratories were utilized. Early in the investigation, it was recognized that the results were equally applicable to the high-temperature service encountered in the operation of turbosuperchargers and jet propulsion engines for aircraft. The work therefore, was closely correlated with the related research programs of the National Advisory Committee for Aeronautics, the U. S. Naval Engineering Experiment Station, the alloy producers, and the manufacturers of the equipment being supplied to the Armed Services. Thus, all types of test data were obtained over a temperature range from 1200 to 2000 F.

Early in 1942, the Armed Services requested an alloy that would give satisfactory service at a temperature of 1500 F and at a stress of 7,000 psi. Six heat-resisting alloys of promise for gas turbine and turbosupercharger service were then available, but none possessed the desired properties at high temperatures. At the termination of the work, nearly one hundred alloys had been tested, and ten or more had been shown to possess properties at 1500 F equal to or considerably better than the original goal of the project. Several of the forged and cast alloys investigated were shown to have as good properties at 1600 F as those originally desired at 1500 F.

Concurrent with the determination of design data at high temperatures for the available alloys and those of similar base compositions developed during the project, two of the laboratories were engaged in studies of the properties of new alloy systems. Limited tests on these new experimental alloys at 1600 F indicate these alloys to be superior in properties to presently available commercial alloys and of great future promise, but additional research work is needed to determine satisfactorily their properties and to develop suitable methods for commercial production.

In addition to the foregoing investigations, a project on metal and ceramic materials for jet propulsion devices was carried out in cooperation with the Armed Services, their contractors, and other NDRC divisions. Under this project, assistance was given on the development of materials of construction for both solid-fuel and liquid-fuel rocket motors.

The research work on developing engineering data on heat-resisting alloys and the welding of these alloys is being continued under the sponsorship of the Office of Research and Invention, Navy Department. A comprehensive fundamental investigation of heat-resisting alloys and ceramic materials has also been sponsored by this agency. This work is closely correlated with the engineering studies now in progress.

WELDING

The welding research program comprised 29 laboratory projects, 14 of which were concerned with the welding of ordnance and aircraft materials, and 15 with ship welding and welded steel ships.

A large part of the programs of two of the principal projects on the welding or ordnance material dealt with the development of methods for welding low-alloy homogeneous armor and the development of a welding electrode which was substituted satisfactorily for the high nickel-chromium alloy commonly used for welding of armor. This development provided not only a means for saving large amounts of nickel and chromium but also an electrode which produced welds with ballistic properties comparing favorably with those made with the high nickel-chromium types. Details of the properties and performance characteristics of this electrode were worked out so that Army Ordnance Department specifications could be written. In the later stages of World War II, work was done also leading to the application of this type of electrode to the repair welding of cast armor. Also studied at the request of the Army Ordnance Department was the low-temperature ballistic performance of welded armor plate in connection with the Canadian Cold Test Program.

Fundamental studies of electrode coatings and the causes of weld metal porosity and underbead cracking were begun, but not completed. Under this project, however, an electrode was developed for the welding of high-strength structural steel such as is used in the fabrication of mobile gun mounts and other ordnance material.

A direct explosion test was developed which holds promise for the easy and economic evaluation of welded armor and of prime plate. Other projects carried out dealt with the development of a ceramic backup strip, the effect of oxygen cutting on the weldability of armor plate, residual stresses in weldments and their relief, and the welding of face-hardened armor.

Five projects concerned with investigating the weldability of alloy steels provided procedures and data of considerable value to industry in the improvement of welding techniques.

Spot welding and flash welding processes were investigated to provide information on which wider application of these fabricating methods could be based. Nondestructive testing methods for welds made by these methods were investigated also under two projects. An interpretation of radiographs of spot welds which was developed under one of these investigations was adopted by the Bureau of Aeronautics, Navy Department, in a specification.

The research program to investigate the causes of failures of welded ship structures and to develop remedial measures was sponsored by the Coast Guard, the Maritime Commission, and the Navy Department. It was still in progress at the close of the war and is being continued under direct Bureau of Ships contracts. Studies completed, however, comprised investigations of welding stresses in laboratory scale specimens as well as the measurement of those in actual ship structures during fabrication and during voyages. Two investigations were completed also on the effect of combined loads on the behavior of ship steel. Continuing projects include studies of the weldability and metallurgical quality of steels for hull construction, the effect of notches and structural discontinuities on the behavior of ship steel, a correlation of laboratory tests with full-scale ship plate fracture tests, and the fatigue of ship welds.

FOUNDRY MATERIALS AND PROCESSES

In order to assist in alleviating overloaded facilities for the manufacture of cast steel products and to make available a portion of the large productive capacity of the malleable iron industry, an investigation of the properties, particularly the low-temperature properties, of malleable iron for use in ordnance matériel was carried out at the request of the Office of the Chief of Ordnance. The results of this investigation provided data upon which the substitution of malleable iron for cast steel could be based.

As in the case of malleable iron, it was believed that steel castings might to some extent replace forgings and thus relieve the pressure on forging facilities. Therefore, a research program on the centrifugal casting method was carried out. This program comprised a survey of the possibilities of the method and the research needs, preparation of a bibliography on centrifugal casting, study of the heat flow in metal molds, study of mathematics underlying the process, and experimental work to develop and extend the process to the production of ordnance matériel. The methods proved successful for the experimental production of trench mortar barrels,

recoil cylinders, and other applications, and were applied in production.

Precision casting methods were investigated also to ease the demand on forging and machining facilities. As a result of this work, the process was adopted by Watervliet Arsenal, the Naval Research Laboratory, the Winchester Arms Company, and others, for the production of war matériel such as intricate parts for artillery and small arms mechanisms, and for other applications which required an extensive amount of hand work in their production.

At the request of Watertown Arsenal, two refractory problems were solved. They involved the development of a substitute for sillimanite in pouring rings and the development of an acceptance test for pouring box refractories.

EXAMINATION OF ENEMY MATÉRIEL

Captured enemy matériel was examined in order to determine significant changes in the composition of materials which might indicate impending shortages in enemy supplies and in order to advise the Armed Services, the Foreign Economic Administration, the investigators on the various Division 18 research projects, and industry of enemy developments that appeared to offer improvements or alternatives in our production or military products.

This project supplemented the work of the Armed Services and was conducted in close cooperation with the Army Ordnance Department Collection Center at Aberdeen Proving Ground, the Naval Technical Air Intelligence Center at Anacostia, and the Air Technical Service Command at Wright Field. In the 215 topical reports issued, 794 individual samples or shipments of diverse nature were covered, ranging from aircraft engines to machine guns.

This project brought to the Armed Services the nation's specialists on materials and their production and made available many of the nation's industrial laboratories for special advice and service.

MISCELLANEOUS MATERIALS FOR WAR

Under this classification are grouped a number of investigations relating to studies of materials used for miscellaneous instrumentalities of warfare not included in the above-mentioned groups.

At the request of the Office of the Quartermaster General, several investigations were undertaken. These comprised the development of noncritical fused inorganic coatings for steel canteens and cooking utensils, the development of plated steel flatware for military use, a study of the proper materials for use in a variety of products required by the Quartermaster Corps, investigation of methods of camouflaging mess gear, and the evaluation of the corrosion-resisting properties of an alloy that had been suggested for quartermaster's items.

The properties of a number of miscellaneous materials were also investigated. These projects included a compilation of the low-temperature properties of metals, the behavior of metals under rapid rates of strain, and the effects of impurities on the ferromagnetism of nonferrous alloys used in instruments.

Although most of the problems involving the conservation, substitution, or processing of various materials were sponsored by WPB, several NDRC research and survey projects in this field were conducted at the request of the Armed Services. The survey projects comprised a comprehensive study of the industrial applications of chromium plating to provide a basis for research on the use of chromium plating in war matériel, an appraisal of a proposed investigation on rivets and rivet steels, a study of the use of rare metals in electrical contacts and the possibility of making substitutions of less critical metals, and a study of methods of reclaiming lead-bearing copper-alloy scrap for re-use. The research investigations relating to conservation and substitution and processing comprised an investigation to develop heat treatments for the National Emergency steels so that these steels could be utilized fully in ordnance matériel, a study of the hardenability of cast alloy steels which provided data of wide applicability in the utilization of alloy steels to attain high strength and toughness, and an investigation of the acceptance tests for plain carbon steel forgings in an attempt to provide information of value in the preparation of specifications for ordnance forgings.

Chapter 1

AIRCRAFT MATERIALS

1.1 INTRODUCTION

THE GREATER part of the NDRC work on aircraft materials was concerned with studies of the use of aluminum and magnesium alloys, principally in sheet form. When the aircraft production program was announced early in 1942, it was obvious that, in order to secure the most effective use of the then commercially available materials, it would be necessary to secure fundamental information on their properties both in service and during processing. The program of this part of the work of Division 18 was organized to secure this information as quickly as possible. At the same time, projects were established to investigate the use of the beryllium-aluminum alloys for aircraft engine parts, the use of substitute materials for aircraft control cables, and the use of mechanical means for the improvement of the properties of aircraft materials by surface pretreatments. The results of this latter project, as the successful use of the surface pretreatment was demonstrated, was applied widely by both the Army and Navy and by their suppliers for many ordnance and naval applications other than aircraft. All this work was coordinated with the work of the National Advisory Committee for Aeronautics and the Office of Production Research and Development of the War Production Board which were supporting extensive research programs in the field of light alloys.

1.2 ALUMINUM ALLOYS

1.2.1 Preliminary Surveys

Before planning a detailed experimental attack on a suggested problem, a preliminary survey usually was made by the War Metallurgy Committee, not only of the literature but also of unpublished information which normally would not have been available but which, in the spirit of cooperation engendered by the war emergency, was freely supplied by industry. Such compilations of available data on aluminum alloys included Survey Project SP-17[a] (NA-119),[b] The Effect of Impurities in Aluminum Alloys,[4] SP-18, Fatigue and Impact Characteristics and Notch Effect in Tension of Artificially-Aged Aluminum Alloys;[5] and SP-15 (NA-137), High-Temperature Properties of Light Alloys.[6,7] The problems involved in the use of aluminum and magnesium alloys at elevated temperatures became more pressing late in World War II, and experimental work on them was taken up under NACA and the Army Air Forces' sponsorship as NDRC was in the process of bringing its research program to a close.

1.2.2 FORMING OF ALUMINUM ALLOY SHEET

The aircraft industry forms a vast variety of structural parts out of strong aluminum alloy sheet using a great variety of forming processes, tools, dies, and methods. These processes for forming aluminum alloy sheet vary from simple stretching, simple bending, etc., to highly complex ones in which the metal has to undergo plastic deformation in many directions, is thinned down in some places, thickened in others, and subjected to various stresses in the operations. These processes have often been empirically worked out for commercial material in a condition of high plasticity, greater strength being later given to the formed part by suitable heat treatment.

However, still stronger parts can be made by forming cold-rolled sheet or preheat-treated sheet. Moreover, several stronger alloys, each with different cold rolling and heat treating characteristics, have become available recently, and no one knows when still further strides will be made along the path of providing still stronger alloys. As fast as the stronger alloys become available and enough is known about their uniformity and reliability to justify their use, the aircraft designer wants to specify their use. The production engineer then must form them and is confronted with the fact that the stronger alloys are, as a rule, less ductile than those he has been forming heretofore. He then

[a] SP numbers and NRC numbers refer to the Division 18 project numbers. Listings of the titles of these with contractual information are presented in Appendix G and Appendix F, respectively.

[b] Numbers in parentheses refer to the Armed Service control numbers. The Armed Service titles of these as well as the Division 18 projects pertaining to each are listed in Appendix E.

has to find out whether his previous processes, methods, tools, dies, etc., will serve or whether they must be modified. He may find that some odd-shaped part wanted by the designer cannot be made at all from the new alloy, in which case there must be time out for redesign. When a new part is made in the shop, dies are made for it. If the new alloy breaks instead of forming properly, or springs back more or less than was anticipated, the dies have to be remade.

Predetermination of the suitability of a given alloy or a given lot of an alloy for plastic forming, or of the applicability of a given process and technique for forming a new part from a known alloy would be a godsend.

Survey of Available Information on Fabricating Aluminum Alloys

To collect and correlate the information available on the forming of aluminum alloys, Project NRC-43 (NA-126), Correlation of Information Available on the Fabrication of Aluminum Alloys, was established at the Case School of Applied Science in January 1943. An exhaustive survey of plant practice showed many gaps in the fundamental knowledge necessary for the effective use of these alloys. Therefore, at a later date, the project was extended to permit investigation of the more important forming operations in the laboratory.

The initial objective of this project was to assemble and to correlate all the available information concerning the materials and methods used in typical and critically forming parts so that the "know-how" could be made more readily available to parts producers, particularly the sub-contractors who were new to this work.

A group of field engineers gathered all the specific information in the aircraft plants on materials used, each step of fabrication, kinds of dies, machines, lubricants, speeds, treatments, rejections, etc. This information was then broken down and correlated.

A system of classification, which was primarily dependent on the geometry of the finished part, was evolved. However, many parts of essentially the same geometry may be made in several ways on different equipment. Also, parts which at first appear to be essentially alike may prove to be sufficiently different in detail to cause them to have separate classifications and different fabrication methods. The classification consists of the following parts:

I Singly curved parts.
II Curved channels.
III Contoured flanged parts.
IV Double curvature smoothly contoured parts.
V Deep recessed parts.
VI Shallow recessed parts.
VII Minor forming features.
VIII Tubing.

Over 100 types of parts were covered in detail, and the correlations show that several noteworthy conclusions can be drawn concerning:

1. Preferred forming method for each type of part.
2. Preferential use of one- or two-step forming.
3. Comparison of different methods on similar parts.
4. Preferred material for particular types of parts.
5. Maximum strains during forming.
6. Some engineering analysis of several forming operations.

Because of the nature of this phase of the work, essentially a survey to find and report facts, it is not feasible to attempt a summary of the results other than to state that the volumes of reports provide a veritable library of forming information and have proved useful to both the engineering and the shop personnel. The following titles of these reports indicate their scope:

Section I, *Classification and Analysis of the Forming of Various Parts,* Volumes I[8] and II.[9]

Section II, *Examples of Fabricating Individual Parts,* Volumes I[10] and II.[11]

Section III, *Summary, Contents, and Index of Sections I and II.*[12]

To supplement its series of publications on production methods, the Production Aids Unit of the Bureau of Aeronautics, Navy Department, republished these reports for wide distribution to aircraft fabricators.

Properties of New Aluminum Alloys

The initial results of the work emphasized also the need for information on the forming limits, properties, etc. Consequently the second phase of work was, at the request of the aircraft industry, centered on the new high-strength alloys. The accumulated data are given in Section IV of the series of reports on the project which cover 24S-T8 sheet,[13] 24S-T8 extrusions,[13] R-301 sheet,[13] XA75S sheet,[14] and 75S sheet.[15] Specific information is grouped under several headings for each alloy, these includ-

ing (1) Mechanical Properties—Metallurgical Relations, (2) Mechanical Properties—Design Data, (3) Physical and Chemical Properties, (4) Production—Forming, (5) Production—Other than Forming, (6) Corrosion and Surface Treatment, and (7) Bibliography and Additional Pertinent Information.

This survey of properties of new aluminum alloys relates to alloys of higher static yield strength and lower ductility than those in past use and still in large current use. Therefore, the corrosion, stress-corrosion, fatigue, notched fatigue, and corrosion fatigue behaviors are discussed where the data were available. Since the strong alloys can be, and almost universally are, clad with a corrosion-preventing layer of pure, or nearly pure, aluminum, major corrosion troubles appear to be preventable.

The fatigue, and especially the notched fatigue, behaviors are insufficiently known. There is evidence that in some of the new alloys fatigue resistance is not better than that of the alloys used previously, although static strength is materially increased. This means that the service of aircraft parts needs to be examined to see whether a design aimed to utilize the improved static strength neglects the possibility that fatigue failure will occur. If so, design should be on a fatigue basis, and the apparent virtues of some of the "strong" alloys might prove an illusion. Extensive fatigue and notched fatigue testing to establish which of the alloys afford the best compromise between static and fatigue strengths is in order, as is the refinement of design to avoid stress concentrations, the absence of which is not particularly material from the static point of view but very important from the fatigue point of view. In this way the use of the statically strong alloys without overtaxing their limited ability to resist fatigue can be further developed.

The series of reports on properties of new aluminum alloys serves as a detailed handbook for engineers and shopmen, collecting the known information pertinent to the application and use of these alloys for aircraft structural components. Because of the nature and magnitude of this work, it serves as a ready cross reference for either the comparison of materials or the selection of a suitable material for a particular application.

Formability Investigations and Development of Test Methods

The third phase of this project was concerned with laboratory studies of the actual formability of several aluminum alloys used in aircraft construction. This involves fundamental considerations of the plastic flow of these materials under widely varying stress-strain conditions, particularly with respect to the more complex stresses, and with strain gradients.

Beginning with the study of simple bends and the allied operations of stretching, both of which subject a uniform and symmetrical metal section to a combined tensile load and bending moment acting in the plane of symmetry of the cross section, the first step in the procedure is the accurate analysis of the stress conditions existing throughout a given operation and the correlation of this with the strains attained. Thus, when the exact conditions are formulated mathematically and checked practically on special equipment, the results should provide a basic engineering tool enabling the prediction of formability.

In the initial experimental phase of the work, preliminary tests and some theoretical analyses of the various factors of the problem revealed that the relations between the external forces and gross movements on one hand and the internal stresses and strains on the other were extremely complex and that there were numerous factors exerting a definite influence on the maximum stretch of the tension fiber at the forming limit. For example, it is generally recognized that a strip or bulky section of the aluminum alloy 24S-0 can be bent to a very small radius, with a local stretch of the order of 100 per cent, while on a thin-walled sheet section, such as an angle with the outer leg in tension, the web or the flange will fail when a stretch exceeding 20 to 30 per cent is attempted. The numerous variables were studied and attempts were made to outline a series of tests in which only one or two variables would be involved in order to determine the relative importance of each. The problem of thus limiting the variables "taxed the ingenuity of the investigators to the limit. They found it rather intriguing that visualizing the fundamental relations of an apparently simple group of forming operations clearly exceeded their capacity."[16]

The reports covering the experimental phase of this project, Section V, are as follows:

Part I, *General Introduction.*[16a]

Part II, *Effects of Non-Uniform Stresses and Strains.*[16b]

Part III, *Stretch Forming of Angles with the Outer Leg In Tension.*[17]

Part IV, *Fundamentals of Pure Bending of an Ideal Plastic Metal under Conditions of Plane Stress.*[18]

Part V, *Simple Bending of Rectangular Shapes by Means of Dies.*[19]

Part VI, *Stretching of Rectangular Bars.*[20]

Part VII, *Experimental Strain Analysis of Bent Rectangular Shapes.*[21]

Part VIII, *Combined Bending and Tension of Rectangular Bars.*[22]

Part IX, *Bending of T-Sections.*[23]

The results of this comprehensive investigation were useful in the engineering and production of aircraft parts. While such information apparently is of primary significance to the engineer and designer, it has two very practical potentialities in the shop: (1) to predict formability limits of the given material, and (2) to apply this toward the engineering of forming dies. These objectives, however, were not attained, since a simple method or methods for evaluating formability in the shop were not yet developed when the project was terminated in September 1945 because of the demobilization of NDRC.

Related projects carried out under War Metallurgy Committee supervision, but classed as process projects and hence under WPB rather than NDRC auspices, were NRC-547, Hot Forming of Aluminum Alloy Parts, and NRC-548, Forming Properties of Aluminum Alloy Sheet at Elevated Temperatures.[3] Since the stronger aluminum alloys are less amenable to cold forming than the weaker ones, and, since operating at somewhat elevated temperature greatly facilitates the forming of magnesium (see Section 1.3.5), it was logical to examine the response of the strong aluminum alloys to elevated-temperature forming. They were found to respond excellently. Indeed, at 400 to 450 F, the strong 75S aluminum alloy forms as readily as does soft 24S-0 at room temperature. Many of the techniques developed for magnesium alloys discussed later in this report should be applicable to the forming of aluminum alloys. Hot forming of the strong aluminum alloys is being utilized in commercial shop practice.

Supplementary to the work on the forming of aluminum alloys, Projects NRC-51 (NA-149) and NRC-52 (NA-150), Plastic Flow of Aluminum Aircraft Sheets under Combined Loads, were established at Carnegie Institute of Technology and Pennsylvania State College to secure information on certain limiting properties of these materials.

Predetermination of ability for plastic forming is no easy matter, as is evidenced by experience in attempting to evaluate the deep-drawing steels. However, it does seem possible to acquire enough understanding of the fundamentals of plastic deformation and of forming processes to decrease appreciably the amount of cut and try necessary, even though considerable must remain.

The first approximation to a criterion of ability for plastic forming, and the one on which the engineer has to rely in the absence of better information, is the elongation determined by the ordinary tension test. However, some alloys, quite ductile by this criterion, will not stand much plastic deformation of certain types, while other less ductile ones will stand an astonishing amount.

In most types of plastic forming, the metal is under biaxial stress, not uniaxial as in the tension test. Biaxial stress can be produced by pulling on the ends of a hollow cylinder while it is simultaneously being stressed by internal hydraulic pressure, but this method is not applicable to sheet.

The initial phase of the research program was the development of a series of laboratory tests capable of evaluating those plastic properties of importance in sheet metal forming operations. Particular emphasis was placed on the plastic behavior of sheet metals under a wide variety of strain combinations. This resulted in the development of several tests, which in combination yield a great deal of useful information concerning the formability of a particular material. These tests are as follows:

Circular Hydraulic Bulge Test.[24] A bulge method was developed in which a round or elliptical bulge or bubble is blown by hydraulic pressure from a sheet anchored at the periphery. Previously, a cross-hatched grid is placed on the sheet by photographic methods. As the bulge grows, the distortion of the grid is measured and the limiting deformation at fracture is noted. From these data and from the thickness at the places where uniform deformation, not necking down at fracture, has occurred, the stress can be calculated. This test had been used to some extent previously to study the ductility of sheet materials, but it was not well understood. In this investigation it was adapted to the study of stress-strain relationships in the plastic range and used to obtain stress curves under balanced biaxial tension, the state of stress being set up in the dome of a circular hydraulically formed bulge.

Elliptical Hydraulic Bulge Test.[25] This test is a

modification of the circular hydraulic bulge test. By altering the shape of the opening over which the bulge is blown from circular to elliptical, it is possible to set biaxial tensile strains, the ratio of which depends on the ellipticity of the opening. Use of the elliptical opening provides strain ratios comparable to those obtained in many practical forming operations.

Microcompression Test.[25] To overcome the intrinsic difficulties in compression testing of sheet materials, namely, the tendency for the ordinary specimen to buckle, a test was designed in which a specimen 0.04 in. by 0.04 in. by 0.12 in. is employed. This test permits the stress-strain curves in compression to be determined for sheet materials of 0.040 in. thickness.

Microtension Test.[25] This test was developed primarily to check against size effect in the microcompression test and utilizes a specimen of 0.04 in. by 0.04 in. corresponding to that of the microcompression specimen. It was possible to demonstrate by means of this test that size effect is absent in the microcompression test described above for commercial aluminum aircraft sheet. In the course of developing these tests, a study was made of the stress-strain relationship for Alclad 24S-0 and 24S-T sheet under combined stresses. It was found that these materials obey a generalized stress-strain relationship in the plastic range.

Direct Tension Tests.[26] In addition to these tests, two direct tension tests were developed which provide complementary information to that obtained in the above tests. In those types of plastic flow where simple stretching of wide sheet is concerned, the uniform stretch, before necking begins, is a criterion of behavior. In other types of flow, such as bending over a sharp radius, the local deformation over a very minute gage length, which occurs during the necking process, is the criterion. The standard ASTM tensile specimen for sheet does not distinguish between these two types of flow. The uniform stretch is hampered by the proximity of the wider grips (the piece is not long enough), and the local deformation occurs over too great a length (the piece is too long). To separate these factors, a long specimen 2 in. wide by 12 in. long in the gage length and a short specimen 12 in. wide by 1 in. long were used. The first specimen yields data representative of that obtained when stretching over long gage lengths, and the second, data representative of that obtained when stretching under conditions of severe lateral restraint. Tests using these two types of specimens were made for Alclad 24S-0 and 24S-T, and flow curves in simple tension were determined for these materials.

When the series of tests just described became available, it was deemed advisable to apply the tests to a study of the ductility at room temperature of the important aluminum sheet metal alloys. This study was carried out for the following materials: 24S-0, 24S-T, 24S-RT, 24S-T81, 24S-T86, 75S-0, 75S-T, R301-0, R301-W, R301-T. All sheets tested were 0.04 in. thick and in the clad condition. As a supplementary investigation, the effect of aging at room temperature on the properties of 75S in the circular bulge test was studied.

The detailed results of this series of tests are covered in Parts II and III of the final report for the project.[27, 28] Certain regularities were observed which can be summarized as follows:

1. Uniform elongation is strongly dependent upon the method of loading. Loading in the circular hydraulic bulge test favors high uniform elongations in the annealed materials in which it is possible for unstable plastic flow to occur.

2. In the circular bulge test, the behavior of the aged materials where instability does not occur varies with the stress-strain characteristics of the material being tested. For very high ratios of yield strength to tensile strength, the uniform elongation in the circular bulge test is considerably greater than in simple tension. On the other hand, for lower yield strength-tensile strength ratios, the uniform elongation is about the same or somewhat less than in simple tension.

3. For annealed materials, the uniform elongation in the circular bulge test is always greater than in the elliptical bulge test. In the heat-treated materials, this difference is still present but is much less pronounced and, in some cases, the results from the tests are quite similar.

4. The local reduction of area for the annealed tension tests is unaffected by lateral restraints imposed in the wide specimen. In the heat-treated materials, however, the reduction of area is considerably lower in the wide test than in the narrow.

5. It was found that 75S-W could not be formed satisfactorily in the circular bulge test because of the strong tendency for the formation of strain markings similar to Lüder's lines which lead to premature failures.

In order to provide a more rational basis for the

interpretation and understanding of these results, a mathematical analysis of some of the conditions leading to unstable plastic flow and rupture was carried out. The role of these factors in establishing forming limits is discussed in Part IV of the final report on the project.[29]

Inasmuch as the most profitable application of data on forming limits can be realized only if some previous knowledge of the critical strains arising in forming a part of given design is available, considerable attention was devoted to this problem. Analyses were developed for the strain distribution in a circular hydraulically formed bulge and an elliptical hydraulically formed bulge, these parts representing pure stretching. The problem of combined stretching and drawing was next considered and an analysis derived for a circular cylindrical cup with a spherical bottom.[30] Good agreement with observed strain distributions was obtained with all these solutions.

These methods allow a better evaluation of the plastic behavior of different aluminum alloys in different conditions of cold work or heat treatment. With a background of experience in the formability of, and die design for forming, a few commercial alloys, the way in which a new alloy will behave under conventional forming methods and existing dies could be predicted approximately from the long and short tensile specimens and the bulge test data.

However, if a new part has to be made, even these data on forming limits may be inadequate, and the best guide will be the "know-how" accumulated from experience with more or less analogous parts with similar types of deformation.

1.2.3 Casting of Aluminum-Beryllium Alloys

A decade or so ago, tests of some small forgings and castings of aluminum alloys containing 20 to 35 per cent of beryllium indicated interesting properties, and rather elaborate plans, which never materialized, were made for relatively large-scale production of sheet and forgings. Sporadic experiments were carried on thereafter, both by producers of beryllium and by producers of aluminum. A particular aim, desired for the aircraft service, was the production of sound alloys of this type, either cast or forged in a size suitable for pistons of aircraft engines. Considerable commercial effort along this line produced nothing but a succession of failures and a belief among those who had worked on the problem that the alloys were not amenable to processing in the size required. Others were not convinced of this and argued that there was a possible chance that more exhaustive experimental work would show how processing might be accomplished.

Because the properties that would be secured if the alloys could be processed were so attractive, the Bureau of Aeronautics, Navy Department, decided to explore this chance. Project NRC-7 (NA-100) (AC-4), Beryllium-Aluminum Alloys for Engine Parts, therefore was established at the National Bureau of Standards, everyone concerned being advised that the prospects of success were very remote.

Much careful work, even trying out methods such as not only melting in vacuum but even pouring in vacuum, led to the conclusion that the commercial investigators were quite correct in their opinions that the alloys are not amenable to processing. Moreover, the reason for this was established as being the long range between the beginning and end of solidification which prevents adequate feeding and, therefore, on first freezing, produces a mass full of shrinkage voids and a matrix that will not withstand forging to close the voids. Only the casting of a very thin layer followed by another very thin layer, and so on, offered any possibilities, and no technique was found by which this solution could be utilized successfully. Various alloying additions were tried with the idea of trying to reduce the long freezing range, but none were successful.[31]

It became obvious that the chances of overcoming the difficulties were so small and so great an amount of work would be required to produce sound masses of the size wanted, if it were ever possible to produce them, that the effort would be far better spent on more practical war problems. The project, therefore, was terminated.

1.2.4 Needs for Research on Aluminum Alloys

Late in World War II, at the request of the Committee on Materials Research Coordination of NACA, a survey was undertaken to determine the

research needs of the aircraft producers with respect to aluminum alloys. Although Project SP-30, Suggested Research on Aluminum Alloys from Members of the Aircraft Industry, was completed after the close of the war, the report[32] outlines the problems that still existed.

1.2.5 Indexing of Division 18 Reports on Aluminum Alloys

An index[33] of the Division 18 reports on aluminum alloys was prepared by the Research Information Division of the War Metallurgy Committee. It gives a subject list of the various projects with the reports issued on each, a brief abstract of each report, and a subject index of the reports. It is believed that this index will enhance the usefulness of the many reports on the subject.

1.3 MAGNESIUM ALLOYS

1.3.1 Introduction

The very slight commercial use so far made of magnesium alloy sheet naturally portends a lack of knowledge of its possibilities and limitations to a degree even greater than exists for the more widely used aluminum alloys. Moreover, magnesium has problems of its own not present in aluminum. The magnesium crystal is not cubic but hexagonal, and this involves the possibility of directional differences in magnesium sheet. Also, the hexagonal crystal is less suited to plastic deformation than is the cubic crystal, so that magnesium alloys as a class cannot be subjected to severe plastic deformation at ordinary temperatures but must be warmed considerably in order to stand even a reasonable amount of such deformation.

While it may be that the corrodibility of magnesium alloys has been overemphasized, some do corrode badly under certain circumstances, and attempts to clad them with a protective metal layer analogous to that used on clad aluminum alloys have not been commercially successful. The possibility of failure of certain magnesium alloys as a result of stress corrosion has come recently to the fore.

Current magnesium alloys are rather notch sensitive, and their static and fatigue strengths are, even on a strength-weight basis, little better, if any, than those of aluminum alloys.

Thus, a multiplicity of unknown or inadequately known factors must be taken into account when magnesium sheet is proposed for aircraft use.

However, enough possible aircraft uses were in sight in which it might be at least a competitor with aluminum to warrant a comprehensive study. Moreover, the existence of adequate production facilities for making the metal was an added spur toward obtaining a true evaluation of its proper position as an engineering material.

In mid-1942 two projects were established to investigate the properties of commercial magnesium alloys—one dealing with mechanical properties and heat treatment, the other, with fatigue properties. Subsequently the program was extended to include studies of the formability and deformation characteristics of magnesium alloys. In March 1943 it became apparent to the members of the War Metallurgy Committee Project Committees for these projects that an independent and comprehensive study of the stress corrosion of commercial magnesium alloy sheet should be made. As a result of this study, a project was established to develop new fabrication methods to minimize stress corrosion in commercial alloys and to develop new alloys less susceptible to stress corrosion.

1.3.2 Mechanical Properties of Magnesium Alloys

At the request of the aircraft industry, the War Metallurgy Committee initiated the establishment of Project NRC-21, Properties and Heat Treatment of Magnesium Alloys, at the University of California. Subsequently, the Bureau of Aeronautics, Navy Department, endorsed this project and actively cooperated in its prosecution under their control number NA-144. The objectives of this investigation were the determination of the effects of size and notches on the mechanical properties of commercial magnesium alloys for aircraft and combat vehicle use, the evaluation of the damping properties of these alloys, and an investigation of heat treating processes with a view to the development of superior properties for these alloys. After the first year of study, the program was extended at the suggestion of the producers of magnesium to include studies of the notch sensitivity of new alloys in sheet, strip, cast, and extruded forms.

Effect of Size Upon Tensile Properties of Specimens of Magnesium Alloy Sheet[34]

Four magnesium alloys (both the hard-rolled and annealed 6½% Al, ¾% Zn alloys and 1½% Mn alloys) were investigated for the effect of size on the tensile properties of sheet. In general, the material investigated was within the manufacturer's stated specifications.

The tensile strength, yield, and percentage of elongation in a 2-in. gage length show very little size effect. The reduction at the fracture section reveals that the percentage of reduction in area and the true breaking stress decrease as the width increases. From the nominal tensile properties obtained, it does not appear that a true size effect exists for the materials investigated. However, narrow specimens exhibit a greater percentage of reduction in width than wide specimens, which indicates that greater local necking down occurs in the narrow specimens. The percentage of elongation in 2 in. does not show any definite variation with size.

The difficulties encountered in industrial practices are probably associated more with gripping and load application than with a size effect of the material.

Notch Sensitivity of Magnesium Alloys[35,36]

In the order of increasing sensitivity to a reamed hole, the alloys tested were hard-rolled 1½% Mn alloy, annealed 1½% Mn alloy, hard-rolled 6½% Al, ¾% Zn alloy, 24S-T aluminum alloy, Alclad 24S-T aluminum alloy, and annealed 6½% Al, ¾% Zn magnesium alloy. The annealed and more ductile magnesium alloys are more notch sensitive than the hard-rolled and less ductile alloys of the same composition. For 1½% Mn alloys, the thin sheets are more notch sensitive than the thick sheets, but for the 6½% Al, ¾% Zn alloys, the notch sensitivity is invariant with sheet thickness. A large increase in sensitivity to the notch occurs as the width of the specimen increases for constant form factor for all alloys tested for this effect (both the hard-rolled and annealed 6½% Al, ¾% Zn alloys and 1½% Mn alloys). The tensile strengths of both notched and unnotched specimens, based on both original and final cross section area, are considerably greater at −318 F than at room temperature. For a condition of very small ductility (annealed 6½% Zn, ¾% Al alloy at −318 F, elongation about 5 per cent, and hard-rolled 6½% Zn, ¾% Al alloy at −318 F, elongation about 1 to 2 per cent) the stress distribution in a notched specimen does not follow that predicted by elastic theory but agrees in general with the distribution existing for a ductile material. Hence, only a very small amount of ductility is required to redistribute completely the stresses at the root of the notch.

The notch efficiencies in tension for American Magnesium Corporation annealed and hard-rolled 3% Al, 1% Zn sheet alloys and the equivalent Dowmetal alloys were evaluated. The notch used throughout this investigation consisted of a single central hole in a tensile test specimen, and the notch efficiency was expressed as the ratio of the net average tensile strength notched divided by the tensile strength unnotched. As in previously reported investigations on other magnesium sheet alloys, it was found that the notch efficiency depended upon the ratio of hole diameter to specimen width for constant width specimens, and the notch efficiency depended upon specimen width when the ratio of hole diameter to specimen width was held constant. The hard-rolled alloys were practically insensitive to a notch except for the wider specimens which were investigated. The annealed alloys exhibited minimum notch efficiencies of about 0.90 for 1-in.-wide specimens at ratios of hole diameter to specimen width of about 0.125 in. As the specimen width increased from 1 inch to 6 inches, the notch efficiency was reduced from about 0.90 to about 0.82. These observations are in agreement with the general trends previously reported for other alloys.

In general, variations in the procedure of producing the hole had little influence on the notch efficiency. Variations in drilling speeds and feeds had no influence on the notch efficiencies. Drilled and reamed holes presented only slightly superior notch efficiencies to those obtained by drilling alone. Other factors such as lubrication, drill design, and drill dullness were investigated.

Difficulties owing to the formation of small cracks were encountered in punching holes in magnesium alloy sheet at atmospheric temperature. These difficulties were overcome by punching the magnesium alloy sheet at elevated temperatures. The optimum temperature at which the highest notch efficiency occurs is unique for each alloy. Complete data for the optimum punching temper-

atures, punch an die design, and clearance were obtained. Under the best combinations of conditions for punching, some alloys exhibited a higher notch efficiency for punched holes than for drilled holes.

Standard dimpling procedures always resulted in cracking magnesium alloys when the operation was carried out at atmospheric temperatures. However, all of the standard magnesium alloys may be satisfactorily dimpled at elevated temperatures. The optimum temperature for dimpling as evaluated by the notch efficiency closely corresponds to the optimum temperature for punching. Each alloy, therefore, exhibits highest notch efficiencies when dimpled at the optimum temperature for that alloy.

The sensitivity of magnesium alloys to scratches is of about the same order of magnitude as the sensitivity of 24S-T aluminum alloy, but it is greater than the sensitivity of Alclad 24S-T.

The notch sensitivities of extrusions of four magnesium alloys (6½% Al, ¾% Zn alloy, 1½% Mn alloy, 8½% Al, ½% Zn alloy, and the 3% Al, 3% Zn alloy) in the "as received" condition were investigated under conditions of axial and eccentric tensile stress. The notch sensitivities of extruded aluminum 24S-T and sand cast magnesium alloy, 9% Al, 2% Zn, were studied for comparison.

Extrusions of the 6½% Al, ¾% Zn alloy, 8½% Al, ½% Zn alloy, and the 3% Al, 3% Zn alloy, like aluminum alloy 24S-T, displayed notch strengthening under axial tension. The 1½% Mn alloy showed little notch effect, while the 9% Al, 2% Zn alloy showed reduction in strength under the notch. Notch sensitivity in the "as received" condition did not correlate with grain size, hardness, elongation in 2 in., stress-strain relationships, or any of the conventional tensile test data.

Under eccentric stress, the strength of notched bars was reduced greatly. The order of notch sensitivity of the magnesium alloys studied, namely, 6½% Al, ¾% Zn alloy, 3% Al, 3% Zn alloy, 8½% Al, ½% Zn alloy, 1½% Mn alloy and 9% Al, 2% Zn alloys in order of decreasing ratio of notched strength to unnotched strength, was the same in axial and eccentric tension. However, aluminum alloy 24S-T showed greater sensitivity to notches under small eccentricities of stress than the 6½% Al, ¾% Zn alloy, the 3% Al, 3% Zn alloy, and the 8½% Al, ½% Zn alloy. In the "as received" condition, the magnesium alloys are similar to aluminum alloy 24S-T in notch sensitivity.

Within the limits of this investigation, prestretching of extrusions of the 6½% Al, ¾% Zn alloy, 1½% Mn alloy, and 8½% Al, ½% Zn alloy resulted in increased ratios of notched strength to unnotched strength.

While the 8½% Al, ½% Zn alloy extrusions in the "as received" and in the solution heat-treated conditions showed notch strengthening, these extrusions showed reduction in notched strength on aging. For this alloy aged "as received," the ratio of strength notched to strength unnotched was about 0.83, but when aged after solution heat treatment, this ratio fell to 0.50. In the heat treatment study, changes in microstructure were found to accompany changes in tensile notch sensitivity.

Damping Capacity of Magnesium Alloys[37]

The mean specific damping capacities of three magnesium-base extrusions, nine magnesium-base sand castings, and seven aluminum-base sand and permanent mold castings were investigated. These investigations indicated that magnesium alloys have rather high damping capacities which may be useful in absorbing energy in freely vibrating systems. These capacities were evaluated and compared with those of aluminum alloys. The high damping capacity of magnesium was correlated with the formation of twins in the material.

Heat Treatment of Magnesium Alloys[38]

The solution heat treatment and aging of the 9% Al, 2% Zn alloy were investigated. Solution temperatures of 770 F to 775 F were found to give the best results. Local fusion occurs in this temperature range but does not become harmful unless temperatures are higher. Preheating does not prevent local fusion and is of no benefit except in overheated specimens. Overheating may be detected by the presence of grain boundary voids in polished specimens. Some heats which manifest coarse grain sizes, presumably as a result of variations in foundry practice, require higher temperatures or longer times for solution treatment.

Direct quenching into hot or cold water from the solution temperature results in cracking, probably because of hot shortness. If bars are cooled to temperatures between 715 and 750 F before quenching, cracking is avoided. This procedure has been called a modified quench. Properties of bars subjected to such a treatment are about the same as those of

bars cooled in air according to the commercial practice. After aging, however, quenched bars develop 10 per cent greater tensile strength and yield strength than bars cooled in air. To develop maximum properties a high degree of solution must be obtained before aging. Coarse-grained castings require special care.

Two modes of precipitation of the beta phase have been observed, a lamellar type growing from nuclei in the grain boundaries and a general precipitation in crystallographic planes throughout the grains. The mode of precipitation does not vary with aging temperature. There are indications that recrystallization of the matrix accompanies lamellar precipitation and that the strengthening effect of such precipitation is small. Recrystallization does not attend general precipitation, which is mainly responsible for age hardening. Less lamellar precipitation results from the aging of bars quenched in hot water than from bars cooled in air or quenched in cold water previous to aging. This treatment minimizes the extent of lamellar precipitation and yields the best tensile properties. It is found that aging time may be considerably shortened, obtaining equivalent results, through substitution of 375 F for the usual aging temperature of 350 F. A new heat treating schedule is recommended consisting of solution treatment, cooling of the furnace to 730 F, quenching in boiling water, and aging for 4 to 5 hours at 375 F.

The data given in the reports cited in the foregoing discussion are of direct value to designers of aircraft and military equipment and it is believed that they will help to extend the use of light structural alloys.

It was evident in the work of this project that the control of grain size in magnesium castings is essential. Work on this, together with much other work on avoidance of microporosity so as to get sound castings and sound forging blanks, was carried on under War Metallurgy Committee supervision, but, since these projects were classified as process research and came under OPRD rather than OSRD auspices, they are not summarized here. The OPRD projects were Project NRC-546, Cast Magnesium Alloys and Existing Foundry Techniques and Practices, conducted by Battelle Memorial Institute, and Project NRC-550, Control of Grain Structure and Its Effect on Quality of Magnesium Alloy Castings, conducted by the University of California.

Other OPRD projects on the fabrication of magnesium were Project NRC-549, Machinability of Cast Magnesium and Magnesium Alloy Ingots, conducted by Battelle Memorial Institute, and Project NRC-552, Production and Properties of Magnesium Press and Hammer Forgings, conducted by the Wyman-Gordon Company.

1.3.3 Fatigue Properties of Magnesium Alloys

To complement the work on the investigation described above, Project NRC-22 (NA-145), Fatigue Properties of Magnesium Alloys and Structures, was established at Battelle Memorial Institute. The aim of this project was not only to determine the fatigue properties of commercial magnesium alloys but also to study the fatigue properties of welded and riveted structures fabricated from magnesium alloy sheet. The program was revised subsequently to include the obtaining of fatigue data on materials supplied by Project NRC-67, Physical and Stress-Corrosion Properties of Magnesium Alloy Sheet, and Project NRC-68, Spot Welding of Magnesium Alloys. The first of these projects is discussed in this chapter of the report, while the latter is described in Section 6.1.4 on welding. Also included in the program was the further exploration of promising methods of joining magnesium and the obtaining of fatigue data on joints other than simple lap joints.

Static notch sensitivity, discussed in Section 1.3.2, and stress-corrosion behavior, to be discussed in Section 1.3.4, tell little or nothing about notch sensitivity in fatigue or about corrosion fatigue.

The unnotched fatigue behaviors of the strong (Al-Zn) magnesium alloys are very much alike, and in the annealed state these alloys are nearly as fatigue resistant as the hard-rolled. The 1½% Mn alloy, hard-rolled, is superior to the other alloys at stresses that require more than 100,000 cycles for failure.

With drilled rivet holes, the 3% Al, 1% Zn alloy is more notch sensitive than the 6½% Al, ¾% Zn alloy or the hard-rolled 1½% Mn alloy. All are more notch sensitive in fatigue than in static tension. But if the rivet holes are filled with "scab" rivets, the fatigue strength rises close to that of a monoblock specimen.

Riveted lap joints failed in the sheet rather than through the holes. The fatigue values are not simply related to the static values and differ with the ratio of static component to alternating component of the load, as well as with the alloy. The fatigue strength was much below that of monoblock specimens. Prediction of behavior, without test, would therefore be difficult. Spot-welded lap joints failed at or near the weld and the fatigue strength was very low, without much difference among the various alloys tested.

Joints made by arc welding under helium (Heliarc) were only slightly better in fatigue resistance than riveted joints in the 1½% Mn alloy, but very much better in the 6½% Al, ¾% Zn alloy. Fatigue strengths of Cycle-Weld joints, made with an organic adhesive, came close to the values for Heliarc welded joints in the 6½% Al, ¾% Zn alloy and were vastly superior in the 1½% Mn alloy. The efficiency of a joint that was merely stuck together was striking, failure occurring in the metal rather than in the joint. However, similar joints made at a later date by the same firm which made the earlier Cycle-Weld joints were inferior, the joint separating. This difference probably related to the care taken or the neglect shown in cleaning the joint surfaces before applying the adhesive. The potentialities of a properly made adhesive joint are vast, and the method deserves intensive development. Of course, room temperature tests do not show how much such joints will behave at higher temperatures where some adhesives of this class tend to soften, or at low temperatures where most of them tend to become brittle. However, static tests show encouraging behavior of some adhesives under extremes of temperature. Once the technique of cleaning the metal and making the joints is under control, high- and low-temperature fatigue studies of these joints would be in order.

Corrosion fatigue tests were made on monoblock, unnotched specimens, using the solution that was selected for static stress-corrosion testing in Project NRC-67, (described in Section 1.3.4) as well as other solutions. The specimens were allowed to corrode, stressed or unstressed, both before fatigue testing and simultaneously with fatigue testing. Naturally, corrosion increases the stress concentration and decreases the resistance to fatigue. Fatigue tests reveal the presence and effect of corrosion before corrosion is detectable by static tests.

The heat treatments developed in Project NRC-67 (described in Section 1.3.4) to prevent static stress-corrosion cracking do not materially affect the fatigue or corrosion fatigue results, and thus the static improvement is achieved without harmful effects from the point of view of repeated stress. Heliarc-welded specimens appear no more sensitive to corrosion fatigue than monoblock specimens.

Details of the experimental work and equipment used are given in three progress reports.[39,40,41] Generalizations of the principal conclusions reached in the final reports[42,43,44] are as follows:

1. An extension of fatigue data on the 6½% Al, ¾% Zn alloy sheet to negative ratios of minimum to maximum stress indicates that, for ratios as large as −0.5, values for the negative ratios fall on smooth curves obtained from positive ratios.

2. Measured stress concentration factors for notches in the 6½% Al, ¾% Zn alloy are lower than those computed theoretically. The measured stress concentration factor depends on the mean load and is lower for high mean loads. It is probable that high mean loads produce some creep which relieves part of the stress concentration.

3. Studies of the effect of precipitation heat treatments which were developed to combat static stress-corrosion on the fatigue strength of magnesium alloys show that such treatments have very little effect on the 6½% Al, ¾% Zn alloys. However, they lower the fatigue strength of the 3% Al, 1% Zn type alloys. These heat treatments do not appreciably alter the corrosion fatigue characteristics of the alloys, although they do affect the static stress-corrosion limit.

4. Some tests which were conducted to find out whether unusually bad corrosion fatigue effects might be associated with Heliarc welds indicate that these welds do not affect the corrosion fatigue strength unfavorably.

5. Cycle-Welded joints vary widely in strength, and the technique of making reproducible joints was not under control in the making of the second lot tested.

1.3.4 Stress-Corrosion of Magnesium Alloys

One of the greatest drawbacks to the use of magnesium alloy sheet materials was the failures of structures by fracture of the sheet through the

mechanism of stress-corrosion cracking. Considerable concern was aroused by the observation that some commercial magnesium alloy sheet structures, under moderate stress and subjected only to atmospheric corrosion, cracked spontaneously. Some of the very striking observations were later found to be due to assembly methods that disregarded the limitations of magnesium, owing to unfamiliarity of workmen with the behavior of the material, but it was nevertheless shown that stress-corrosion cracking could occur.

To bring out the vital problems and determine the research needs in the subject of stress-corrosion cracking of magnesium alloy sheet, Survey Project SP-12, An Investigation of the Present Status of Magnesium Alloy Sheet in the Aircraft Industry, was established in March 1943 by the War Metallurgy Committee at the suggestion of representatives of the aircraft manufacturers. This was an engineering survey covering commercial information much of which was confidential company information on the limitations of magnesium alloy sheet.[45]

The principal undesirable properties of magnesium alloy sheet for aircraft construction were susceptibility to stress-corrosion, low compressive yield strength, extreme notch sensitivity, wide variations between minimum specification values and those of the majority of the stock received, tendency for mechanical properties to become lower on cyclic loading, and anisotropy. With respect to these undesirable properties, the 6½% Al, ¾% Zn alloy was the poorest and the 1½% Mn alloy the best, with the 3% Al, 1% Zn alloy being intermediate. Unfortunately, the 1½% Mn alloy has the lowest mechanical properties of all, although it is the best in most other respects. The British and the Germans seemed to have solved their problems by using alloys similar to the 1½% Mn exclusively. However, there are no indications that they used magnesium alloy sheet for highly stressed primary aircraft structures.

Of all the objections to the use of magnesium, its susceptibility to stress-corrosion cracking is the one that makes its use for critical parts questionable. Most of the other weaknesses can be overcome by design changes, but it appears that stress-corrosion cannot be overcome by structural engineering techniques alone.

The most probable theory for stress-corrosion cracking seemed to be that at ordinary temperatures stress favors the separation of material which would otherwise remain in solid solution. If this separated material, or precipitate, comes out on grain boundaries, it can be corroded away more readily, leaving a branching stress-raising void between the external grains, at which cracking may start. If, by changing the composition, the material can be kept in solution or if it can be precipitated diffusely within the grains where corrosion cannot reach it, the material should be immune to stress-corrosion cracking.

In an attempt to cope with the stress-corrosion problem, Project NRC-67 (NA-147), Physical and Stress-Corrosion Properties of Magnesium Alloy Sheet, was established at Rensselaer Polytechnic Institute in June 1943. The original objectives of the project were to study (1) the variations in the physical properties of available commercial alloy sheet with a view to reducing the spread in physical properties which retard the adoption of this material by designers in the aircraft industry, (2) the effect of aluminum and zinc on the susceptibility of the resultant alloys to stress-corrosion, (3) the effect of variations in aluminum and zinc content on the mechanical properties of sheet material and the possibilities of their improvement by heat treatment, and (4) new alloying additions and their effect on the mechanical properties and resistance to stress-corrosion.

Obvious difficulties arose in the rapid correlation of the results of any selected laboratory test for propensity toward corrosion cracking and behavior under long-time atmospheric corrosion. This was handled by assuming that, if a laboratory test were made using some chemical solution which produced the same type of failure as had occurred in the atmosphere and an alloy or a treatment found that would withstand stressing above normal design loads in such a solution without failure, that alloy or treatment would probably be immune in atmospheric service. It was recognized that the elapsed times for relatively early failures in such a test might not be commensurate with the probable life in actual service. Therefore, such test could not be interpreted quantitatively, though there should be some qualitative indication of how different variables were influencing the tendency toward, or away from, stress-corrosion cracking.

It was necessary, therefore, to make a comprehensive study of methods for determining the re-

sistance to stress-corrosion and to correlate the results of each method. This resulted in the establishment of laboratory procedures for investigating the problem of improving the physical and stress-corrosion properties. It was found that in cold-rolled commercial stock a stress relief anneal at 350 F for 2 hours greatly mitigated corrosion cracking without seriously impairing other properties. Subsequently, cold rolling to about 20 to 30 per cent reduction followed by a 250 F stress-relieving treatment was found to produce metal with a minimum tendency toward stress-corrosion cracking and with mechanical properties at least as good as those produced by the earlier, conventional methods. This afforded a solution to what at first appeared a problem most difficult to solve.[46] In addition to studying various heat treatments, rolling procedures, and combinations of the two, the effects of various surface treatments on stress-corrosion were also investigated.[47] These included anodic treatments, selenium treatment, dichromate treatment, and shot peening.

The first phase of the studies of the development of alloys with improved mechanical properties and resistance to stress-corrosion involved investigating the effects of minor addition agents and minor variations in melting practice on the properties of alloys of the 6½% Al, ¾% Zn and 5% Al, 1% Zn types. In this work, observations were made that agreed with those made under Project NRC-70, discussed in Section 1.3.6, as to the desirability of pure metal, that is, metal presumably free from oxide. Although improvements were made in the resistance to stress-corrosion of alloys of the 6½% Al, ¾% Zn and 5% Al, 1% Zn types, alloys with a new high level of mechanical properties were not developed.

Studies were then started on the development of new alloy compositions with improved properties. This was approached by investigating precipitation hardening in alloys of widely varying compositions. The response to precipitation hardening treatment was evaluated through hardness tests.

It was found that additions of Cd and Ce together caused precipitation hardening and that additions of Ag to Mn-Al-Sn alloys improved precipitation hardening. Encouraging results were obtained with Mn-Zn and Mn-Zn-Zr alloys. This work was incomplete when the project was terminated in October 1945 in accordance with NDRC demobilization plans. It is being continued under a direct contact with the Materials Laboratory, ATSC, AAF, Wright Field. Research on the development of new magnesium alloys with improved properties is also being sponsored by the Bureau of Aeronautics, Navy Department.

1.3.5 Forming of Magnesium Alloy Sheet

Another obstacle to the use of magnesium alloy sheet in aircraft construction was the lack of knowledge of its forming properties. Owing to the very limited use of magnesium as a material of construction and almost complete lack of experience in its use in fabricating aircraft, it was imperative that data be obtained as expeditiously as possible which would be of value to the designers and fabricators in determining the possibilities and limitations of these alloys.

At the insistence of the aircraft industry, the War Metallurgy Committee initiated the establishment of two projects, one dealing with studies of formability and the other with fundamental information on deformation characteristics. Subsequently, these projects were endorsed by the Bureau of Aeronautics, Navy Department, and their control numbers were assigned.

Project NRC-44 (NA-146), Formability of Magnesium Alloy Sheet, was established at the University of California in December 1942 with the objective of establishing design limitations and improving press and deep-drawing techniques. The program included the determination of variable speed stress-strain characteristics of magnesium alloys, minimum bend radii in rubber-press forming, and the limits of the deep drawing of cups. This program was later extended to include studies of the forming of stretch flanges, beads on flat panels, shrink flanges by hydropress forming, and stretch forming of contour panels.

Elevated Temperature Variable Speed Tensile Tests[48]

The most important fundamental data for the evaluation of the formability of metals is obtained from stress-strain curves. The formability of magnesium alloy sheet is limited at atmospheric temperatures, but it is sufficiently improved at elevated temperatures up to 700 F to make severe forming

feasible. At the elevated temperatures, however, the strain rate influences the plastic flow curve. Therefore, in order to provide adequate data for the determination of the formability of magnesium alloy sheet, flow curves were obtained for strain rates of about 10 inches per minute up to approximately 140 inches per minute over the useful range of forming temperatures from 70 to 700 F. These data are directly useful in determining the sizes and dimensions of parts attainable in a number of the common forming operations.

Grid analyses of the specimens yielded data for evaluation of the strains obtainable over various gage lengths for all conditions of strain rates and temperatures which were studied. These data provide the numerical values that are essential in determining minimum bend radii and in determining values for stretching operations in general.

Forming of Bends on the Guerin Press[49]

The minimum bend radius for forming straight flanges of magnesium alloys at atmospheric temperatures is too great for aircraft forming requirements. Elevated temperature forming not only provides the possibility of producing adequately low minimum bend radii but also reduces the springback. The investigation on bending provided the essential design data for forming straight flanges over temperatures from 70 to 450 F for six standard magnesium alloy sheet materials.

Evaluation of Deep-Drawing Properties at Elevated Temperatures[50]

The deep-drawing properties of annealed 1½% Mn alloy, 3% Al, 1% Zn alloy, and 6½% Al, ¾% Zn alloy at elevated temperatures were determined by deep drawing cylindrical cups. The drawability was evaluated in terms of the maximum diameter and the maximum cup height which could be drawn successfully. Effects of punch radius, die radius, clearance, hold-down load, punch temperature, and die temperature on the drawability were investigated.

At room temperature only shallow draws are possible. At 500 F improved drawability is obtainable, and at higher temperatures very deep draws can be produced. The highest drawability at elevated temperatures was obtained with a heated die plate and hold-down pad and a water-cooled punch.

On the basis of hot shortness and excessive grain growth, the maximum permissible drawing temperatures of about 700 F for the 1½% Mn alloy, 850 F for the 3% Al, 1% Zn alloy, and 800 F for the 6½% Al, ¾% Zn alloy were tentatively established. At these temperatures the maximum percentage of draws obtained by using a water-cooled punch were approximately 67½% for the 1½% Mn alloy, 67½% for the 3% Al, 1% Zn alloy, and 65% for the 6½% Al, ¾% Zn alloy.

Forming Shrink Flanges in the Guerin Press[51,52]

Many aircraft parts consist of a flat web with a convex flange, generally produced on the Guerin press. The forming action consists of bending the flange around the die bend radius and simultaneously shrinking the outer fiber of the flange from the original length in the blank to its length when the flange contacts the die. The maximum successful shrink obtainable depends on several factors.

1. For a 360-degree flange, the flange height must be sufficiently small to prevent buckling of the flange.
2. The die bend radius must be sufficiently large to prevent bend cracking.
3. The pressure must be sufficiently great to permit complete forming.

The improvement in shrink flange formability of magnesium alloys, in which buckling gives the forming limit for segment lengths 8 inches or greater, is minor at forming temperatures up to 450 F. The investigation demonstrated that considerable improvement can be achieved, however, for room temperature and elevated temperature forming, if cutouts are used and if the resulting segment lengths are made about 2 inches in length or shorter. The increase in percentage of shrink for decrease in segment lengths is greater at elevated temperature forming than at room temperature forming. The shrink flange formability at 450 F for the 0.040-in. sheet is best for the annealed 1½% Mn alloy and the poorest for the annealed 6½% Al, ¾% Zn alloy. The hard-rolled 6½% Al, ¾% Zn alloy, the hard-rolled 1½% Mn alloy, the annealed 3% Al, 1% Zn alloy, and the hard-rolled 3% Al, 1% Zn alloy give intermediate results. The percentage of shrink which may be achieved for all segment lengths decreases with an increase in the die contour radius.

Springback of the flange in shrink flange forming proved to be approximately the same as that for

straight bends for the forming temperatures and ratios of die bend radius to sheet thickness investigated.

Forming Beads in the Guerin Press[53]

The major factor which determines the maximum forming limit of beads is the maximum strain which may be achieved over the bead contour. Under all conditions which were investigated, it was found that the atmospheric internal beads fracture at or near the point of tangency of the circular portion of the bead contour and the die bend radius. At the point of tangency local deformation was observed consistently for all test conditions. Grid analyses revealed that the strains are essentially uniform over the entire circular portion of the bead contour. Maximum design limits were calculated from the grid analyses.

The maximum uniform strains which can be achieved were found to increase with an increase in the forming temperatures up to 300 F. A decrease in the maximum permissible strain was observed at 450 F as compared with that at 300 F for all alloys except the annealed 1½% Mn alloy and hard-rolled 3% Al, 1% Zn alloy. Also, greater uniform strain can be achieved with beads formed on external beading dies than those formed on internal dies at the forming temperature of 70 F. The formability of magnesium alloy beads on external dies proved to be so good for most alloys at 70 F that no tests were run at elevated temperatures.

Stretch Forming[54]

The maximum permissible limits for the stretch formability of six magnesium alloys were determined for a series of singly and doubly convex parts and also for a series of saddleback parts. The maximum permissible stretch at 70 F was small. At this temperature, stretch forming was found to be limited to contours where the maximum contour line is only a few per cent greater than the minimum contour line. The maximum permissible stretches were found to increase with increasing temperature over the range of temperatures investigated. At 300 to 400 F, high stretches were successfully obtained and severely contoured doubly convex and saddleback parts were easily fabricated. Elevated temperatures also minimize the occurrence of grip failures and the presence of buckles in saddleback parts.

The average stretches which were obtained exceeded the uniform strain obtained in tension tests by wide margins. These data reveal that, contrary to prevalent opinion, the limits of stretch formability are not dependent upon the uniform strain as obtained in a tension specimen, but frequently exceed this value. In several examples, strains approximating the local ductility for the existing stress ratios were obtained over several inches of the maximum contour lines. The effect of die contour and friction are very important in influencing the maximum permissible stretches. Under ideal conditions of control of friction by means of lubrication and grip adjustment, it may be possible to approximate the local ductility along the total length of the maximum contour line of the die.

This project was carried out as an engineering investigation and provided much information on the requirements as to die design, press capacity, technique of carrying out operations at the proper temperature, considering the practical limitations, and on the way in which the different commercial alloys behave in response to many important variables. While some cut-and-try methods will still be necessary in working out forming conditions for specific parts, a study of these reports should vastly decrease that necessity. They tell a good deal about how to form a part, but information on how that part may be expected to stand up in aircraft service was still scanty. Again, since extended actual aircraft use was lacking, reliance had to be placed on laboratory data.

Two advisory reports bearing on the forming problems were submitted by the War Metallurgy Committee at the request of the University of California where they had been prepared as theses for advanced degrees.

The first, *Effect of Combined Stress on the Ductility of Metals*,[55] reviews the existing knowledge on the subject and presents a method of calculating permanent strains at fracture under combined stresses when (1) the stress combination at the beginning and end of plastic deformation and (2) the work hardening effects, are known. The calculations based on the theory presented are in good agreement with the experimental data.

The other report, *Stress-Strain Relationships for J_1 Magnesium Alloy Extrusion under Biaxial Stress*,[56] presents a study of some of the fundamental assumptions of the theory of plastic flow under combined stresses. Few data are available on the

flow of metal under arbitrary conditions of stressing or straining, but this investigation indicates that good predictions of the strain are possible from a knowledge of the true stress-strain curve in tension and the known stress path.

1.3.6 Deformation Characteristics

By analogy to the other hexagonal metals, notably zinc, it was indicated that the difficulties encountered in the failures of magnesium alloy sheet might be due to the unusual deformation characteristics of this type of metallic structure. To obtain fundamental information on the relation between the internal structure of magnesium alloys and their ability to take deformation, Project NRC-70 (NA-148), Deformation Characteristics of Magnesium Alloys, was established at Carnegie Institute of Technology in June 1943.

By means of X-ray and microscopic methods, the crystallographic and metallographic structure of magnesium was correlated with its deformation characteristics. This necessitated the development of a special etching technique which would at once reveal both the grain structure and the twinning due to mechanical working.[57]

The program of the investigation embraces two problems: (1) investigation of the mechanics of deformation in sheets, covering slip, twinning, crack propagation, microstructure, and preferred orientation, and their relation to physical properties; (2) investigation of possible presence of embrittling agents, perhaps oxide films in the metal, or possibly nitrogen, carbon, sulphur, chlorine, or other impurities, and exploration of the possibility of producing more ductile material by the elimination of them.

The work indicated that avoidance of directional properties in sheet that result from the tendency of magnesium to form twin crystals can be achieved by the right combinations of hot and cold work. It was demonstrated that twinning depends on the speed and temperature of deformation, decreasing with increasing temperature and decreasing speed of deformation. The pronounced change in orientation (86 degrees) which is produced by twinning, combined with the above knowledge, was employed to produce randomly oriented magnesium sheet. The tensile strength of this sheet was slightly lower and the reduction of area slightly higher than that of commercial sheet. Such randomly oriented sheet may be desirable for certain operations where isotropy is of prime importance. However, the extreme ease with which the twinning takes place at room temperature, returning the sheet to its normal orientation, makes extremely doubtful the production of magnesium sheet with any marked improvement in room temperature properties by alteration of orientation of its crystals. Furthermore, the production of randomly oriented sheet may complicate rolling practice. Twinning occurs less readily at elevated than at room temperature, but, under rapid deformation in forging or rolling, it may occur even at elevated temperature.

Different lots of magnesium and the same lot cooled at different rates after freezing fracture in different ways, that is, either intercrystalline or transcrystalline. Intercrystalline fracture is thought to denote less dependable material. Metallographic studies revealed the presence of an impurity in magnesium melted from distilled crystals. It was suspected that this impurity was thrown out of solution during cooling, and that when the precipitation occurred at grain boundaries, it was the cause of intercrystalline fractures. Sublimation studies at 480 C in a vacuum of 0.005 micron indicated the presence of thin films, believed to be MgO, located at the grain boundaries and extending in from the thicker film of MgO that forms the outer surface of the sample. The problem of producing metal or purifying it so it is free from such impurities thus appears to be of basic importance. Certain degrees of deformation prior to heat treatment accentuate the propensity for the impurities to separate at the grain boundaries where they are harmful.

Although incompleted, this project was not extended because at that time, November 15, 1944, it was felt that it could not be completed in time to be of value in World War II. Five progress reports[57,58,59,60,61] give the details of the experimental work, and a final report[62] summarizes the results of the investigation.

1.3.7 Status of Research on Magnesium Alloys

In addition to the work done by NDRC, considerable research was carried out on magnesium alloys during World War II by the magnesium pro-

ducers, the aircraft industry, the Armed Forces, NACA, and OPRD. The NACA Committee on Materials Research Coordination compiled a listing of these research projects and, in order to determine the research needs that required attention, requested the War Metallurgy Committee to review the projects completed and being carried out and to make comments and suggestions as to research that should be undertaken.

In February 1945, the War Metallurgy Committee established Survey Project SP-26, A Survey of Research on Magnesium Alloy Being Conducted by Government Agencies, Branches of the Armed Services, and Producers and Fabricators of Magnesium. The report on this project[63] comprises three major sections: (1) a summary of the current and currently interesting research projects on magnesium, (2) suggestions and comments on this research and on magnesium, obtained from those interested in the use of the metal, and (3) a recapitulation of the first two sections, with suggestions as to which research and development work appears to be most necessary to make magnesium a more useful metal.

A digest of the report led to the following generalizations of the research needs in magnesium alloys:

1. The greatest need appears to be for improved magnesium alloys for wrought products, especially sheet. The features most desired for aircraft applications are: less sensitivity to stress-corrosion cracking; higher mechanical properties, particularly tensile and compressive yield strengths; lower notch sensitivity; decreased flammability; greater ductility and the ability to be cold-worked.

2. An observed impurity in "pure" magnesium should be studied for its influence on the present alloys and on any new alloys which may be developed, with the idea that this impurity may be potent in determining the properties of these alloys. Methods of removing or controlling this impurity during the melting of the alloys should be investigated.

3. There is a need for the engineering development of experimental units employing magnesium to be used in evaluating the serviceability of magnesium structural parts and to serve as a source of engineering information for those interested in applying the metal.

4. The development of improved melting methods and molding techniques presents the best approach to the eventual production of higher quality, lower cost, sand, permanent mold, and die castings.

To make available the information collected in this survey to universities and to other research agencies contemplating research on magnesium alloys, in September 1945 the NACA Committee on Materials Research Coordination requested the War Metallurgy Committee to appoint a special committee to review the above-described report and to point out where additional research might be warranted or where the scope of the existing project might be expanded to advantage. An unclassified supplementary report[64] was issued covering the specific topics upon which research is recommended. The NACA Committee on Materials Research Coordination proposes to reduplicate this report for wide circulation in order to promote research on magnesium in the fields of greatest importance at this time.

1.3.8 Indexing of Division 18 Reports on Magnesium Alloys

An index[65] of the Division 18 reports on the magnesium alloys was prepared by the Research Information Division of the War Metallurgy Committee. This index covers the subject list of the various projects with the reports issued on each, a brief abstract of each report, and a subject index of the reports. Also included is a table of the commercial magnesium alloy symbols and compositions. This index should add to the usefulness of the many reports on the subjects.

1.4 MISCELLANEOUS MATERIALS

1.4.1 Control Cables

In December 1941, the Coordinator of Research and Development, Navy Department, suggested that NDRC initiate investigations to develop aircraft control cables with improved wear resistance. The cable which was being furnished to the Bureau of Aeronautics in accordance with Navy Specifications ANRRC-43 and ANRRC-48 was fabricated from 18-8 stainless steel or tin-coated carbon steel. A number of failures had been reported after 100 to 150 hours in service, while in other cases the service life was from 800 to 1,000 hours. The Navy Department was interested in determining the causes of these failures as well as in developing satisfactory

cables from noncritical materials. A brief program of investigation was to be conducted at the Naval Aircraft Factory to obtain some information on the problem. Owing to time limitations and lack of facilities at the Naval Aircraft Factory, the program could not cover the entire field. Consequently, the Office of the Coordinator of Research and Development requested that NDRC undertake a comprehensive investigation. After meetings between representatives of the War Metallurgy Committee, the Bureau of Aeronautics, and John A. Roebling's Sons Company, the largest producers of aircraft control cable for the Navy, Project NRC-15 (N-101), Corrosion-Fatigue Failure of Aircraft Control Cables, was established in May 1942 in the research laboratories of John A. Roebling's Sons Company.

The original program embodied the determination of the effects of composition and operating conditions on the performance of control cables as shown by standard wire cable fatigue tests, corrosion fatigue tests, and low-temperature fatigue tests. Since this original program was designed for the development of improved cables using 18-8 stainless steel wire and since the supply of alloying elements for stainless steel was becoming more critical, the program was modified to include the investigation of galvanized carbon steel cables, as well as cable lubricants for low-temperature service. The program was subsequently extended to include the determination of cable performance with actual service loads and sheaves for the purpose of obtaining data which could be used in the design of aircraft control systems.

Among the various factors affecting the fatigue failure of control cables are the tension on the cables as installed, the ratio of sheave diameter to cable diameter, the material of the sheave, the number of wires in the cable and their arrangement within it, the material of the wires and their surface (plain or coated), the corrosive conditions to be met and the protection against corrosion, the temperatures involved, and the lubricants within the cable.

The cable sizes investigated were $\frac{1}{8}$ in., $\frac{5}{32}$ in., $\frac{3}{16}$ in., $\frac{5}{16}$ in., and $\frac{1}{4}$ in. in diameter with a 7 by 19 construction, and $\frac{3}{32}$ in. with a 7 by 7 construction. The materials included 18-8 stainless steel and carbon steel, bright, galvanized, tinned, and lead-alloy coated. The galvanized cables were made of wire with various weights of hot galvanized and electrogalvanized coatings. Standard commercial lubricants and special lubricants containing lithium soap grease, mineral oils, paralketone neutral base, rust preventative, and extreme pressure additives were studied.

The fatigue and internal friction properties of cable as affected by corrosion in a salt atmosphere and by temperatures ranging from +160 F to −65 F were studied. The fatigue properties of cables were investigated under normal laboratory conditions with sheaves and loads similar to those used in aircraft control systems. The results of these tests with 1 per cent loads showed that under the severe conditions of a salt atmosphere and at −65 F, 18-8 stainless steel cables were the most effective. However, without corrosion and at room temperature, carbon steel cables are equal to or better than stainless steel cables. Service load fatigue tests in the absence of corrosion showed that 18-8 stainless steel has a considerably lower fatigue life than galvanized carbon steel cables. Heavy galvanized cables are the best of the carbon steel cables for corrosion fatigue but have the poorest fatigue life at −65 F. The tin-lead alloy and light zinc coatings did not materially improve the corrosion fatigue life of bright carbon steel cables. The tinned cables had the lowest internal friction in the absence of corrosion. Corrosion by salt spray increases the internal friction of tinned cables and decreases that of heavy galvanized cables. The continuous flexing of the cables during fatigue test in the absence of corrosion lowers the internal friction of the galvanized cables but not sufficiently to equal that of the tinned cables. The internal friction of cables increases with an increase in cable tension and a decrease in sheave diameter.

The fatigue and internal friction of cables are improved by the use of lubricants. The effectiveness of lubricants is dependent upon the temperature and the protection which they afford against corrosion. The commercial cable lubricants are affected considerably by temperature, whereas some of the greases perform quite uniformly over the range of temperatures investigated. Externally applied paralketone (An-C-52) is very effective in providing protection against corrosion, but it becomes brittle at −65 F and flakes off the cable where it bends over a sheave.

The service load tests with micarta and 24S-1 aluminum alloy sheaves indicated that for a given cable tension the fatigue life was satisfactory provided the ratio between the sheave diameter and

cable diameter was above a critical value. The critical sheave ratio increases with the cable tension. For a 1 per cent load, the critical sheave ratio for 7 by 19 galvanized cables is approximately 10; for 10 and 20 per cent loads, the ratio is approximately 20 and 28, respectively. The relationship between the visible wire breaks and the average loss in strength was investigated, as well as that between the loss in strength and the number of reversals in fatigue under various load conditions for 7 by 19 galvanized cables. The fatigue life of 7 by 7 construction cables with 1 per cent loads is less than that of 7 by 19 construction cables with the same loads and sheave ratios.

The AN-210 micarta pulleys operate satisfactorily under relatively low service loads, but under higher loads they fail by wear, splitting, or bearing failures. The 24S-T aluminum alloy sheaves equipped with large ball bearings operate satisfactorily under loads up to 60 per cent of the specified cable strength.

The results of the investigation are summarized in the final report[66] on the project, while the progress reports present the many details of the investigation, covering integral phases of the investigation as follows: the effect of lubrication on fatigue properties,[67] the effect of metallic coatings and lubricants on fatigue properties,[68] the effect of sheave diameter on fatigue life,[69] the effect of metallic coatings and lubricants on fatigue and internal friction,[70] fatigue tests under service loads,[71] and miscellaneous tests and the examination of German and Japanese aircraft cables.[72]

From the experiments made and data presented, the mechanical details and the proper type of lubrication for satisfactory service are made clear. The choice of cable material will vary according to service conditions. This comprehensive work has materially clarified the problems of design of control cable installations and the methods of testing the cable to insure reliability and long life.

1.4.2 Surface Prestressing of Metallic Materials

During World War II, considerable progress was made toward the application of fundamental knowledge to problems of practical significance. A characteristic example of this type is the wide application of surface peening, the basic theory of which had been developed between 1920 and 1930 with little support from industry.

It has been known that cold working the surface of a part greatly increases its endurance under conditions of repeated stress, which are of such nature that failure tends to start at the surface. In analogous fashion, carburizing or nitriding the surface increases its endurance as long as cracks do not start in the hard surfaces. However, it is known also that the cold-worked surface can be over-cold worked to such an extent that cracks are formed, in which case the cold work can do more harm than good.

The advent of high-frequency surface hardening and of flame hardening brought the realization that surfaces can be hardened and strengthened by these means much more rapidly than by carburizing and nitriding.

Surface peening by impact of hard balls, the "cloudburst hardening" method, had been used more as a method of evaluating uniformity of hardness than as a processing method for improvement, though the latter aspect was given some attention.

Springs normally are very highly stressed, and their fatigue behavior is governed by the condition of their surface. Automotive valve springs were especially prone to failure. In 1926, an epidemic of valve spring failures in one motorcar was overcome by shot peening. Shot peening of springs used for individual wheel suspension on automobiles soon followed with gratifying results. Surface peening had proved to be effective in increasing the fatigue life of some machine parts at their operating loads by 200 to 1,500 per cent.

These commercial examples brought to the attention of the automotive industry the value of cold working the surface of parts subject to fatigue. In that industry, some individuals became enthusiastic about the possibilities of shot peening and, through many articles in technical journals, a missionary campaign had been carried on for its more widespread application.

In order to determine the possibilities and limitations of surface peening for the improvement in service life of engine and structural parts of airplanes, the Bureau of Aeronautics, Navy Department, requested NDRC to initiate investigations on the subject. Two projects were established, one on shot peening and one on induction hardening.

Shot Peening

Project NRC-40 (NA-115), Effects of Shot Blasting on Mechanical Properties of Steel, was carried

out by the Research Laboratories Division of General Motors Corporation. The objective of this project was twofold: (1) to correlate and develop principles for the practical application of mechanical surface treatments by a study of their effects on the properties of different materials in various sizes, and (2) to develop techniques for the mechanical surface treatments of certain specific engineering parts such as engine connecting rods, propeller blades, fusion steel weldments, landing gear castings, etc.

For the most part, the investigation comprised (1) the experimental shot peening of numerous parts of military equipment and a substantial number of laboratory specimens which then were tested, largely in other laboratories, and (2) the assembly and consolidation of pertinent data into case histories. The effect of shot peening was determined on fatigue durability, static strength, impact, dimensions, hardness, friction, stress-corrosion cracking, corrosion, surface roughness, and surface failure. Studies also were made of the shot-peening process and equipment and methods of measuring the intensity of peening.

The principal generalizations on the effects of shot peening on the properties of various parts[73,74,75,76] are as follows: (1) fatigue properties are improved, (2) there is little influence on static strength, (3) the effect on resistance to impact is not determined fully, (4) the effect on hardness is not established fully, although there is an indication that hardness may be increased slightly, (5) frictional properties of sliding surfaces are somewhat affected, (6) the tendency toward stress-corrosion cracking of brass and magnesium alloys is reduced, (7) general corrosion is not reduced, (8) the roughness of the surface of shot-peened steel varies in depth up to 0.0040 in. depending upon the shot size and peening intensity used, and (9) its influence on surface failures such as pitting, galling, scuffing, scoring, and fretting corrosion is not yet established.

A major difficulty in the application of shot peening has been knowing when to stop, that is, ascertaining to what degree peening should be carried to secure optimum results and yet to preclude overcold working and the starting of cracks. This is still a difficulty, and the performance, in actual or simulated service, of parts peened to different degrees is the final criterion. Once this is known, directly or by analogy, the degree of peening can be regulated to produce the optimum by subjecting one side of a standard test strip of a standard steel to the intensity and time of peening it is desired to use on the part in question and by noting the amount of bowing that is produced.

The conditions of greatest applicability of surface cold working occur where a part is failing after relatively few applications of repeated stress, the stress being at a very high level, considerably above the endurance limit of the material. Such high stresses may have to be applied because of an initial design error, and because space limitations permit no opportunity to redesign to bring the stress down to a proper level. However, a limited life may be accepted for the sake of saving weight. Because of this, the comparisons of peened versus nonpeened parts are often made at a single level of repeated stress in terms of life at that stress rather than over a range of stresses such that endurance limits would be determined. In terms of life, a stress often can be chosen just above the knee of the fatigue curve such that the increased life appears most phenomenal and spectacular, but around the knee of the curve, duplicate determinations often show very wide scatter and more than a few tests are needed to establish the true life expectancy. While a selected test stress may, therefore, give an exaggerated picture of the real improvement, there is plenty of evidence that in the cases where surface hardness is helpful, the improvement is decidedly worth while.

After the project had been in progress about a year, it became evident that the practical achievements were contributing more to the war effort than the more fundamental research work. Therefore, emphasis was shifted to "trouble shooting," namely, (1) giving service to war production plants in overcoming failure of machine parts by surface treatment, thus avoiding changes in design or tool equipment, (2) increasing the fatigue strength of machine parts, thus permitting increase in power input, and (3) reducing the labor in finishing machine parts by eliminating polishing and manual operations.

A few applications were not helpful or were of doubtful value. Magnesium alloys subject to stress-corrosion were shot peened, but particles of iron from the shot greatly accelerate general corrosion and are difficult to remove. The remedy was to use glass beads instead of iron shot. Shot peening of light armor plate did not improve its ballistic behavior. On some parts of a severely notched contour, tested

in impact, the hardening of the surface was no help. On others, more smoothly contoured, it was useful, one peculiar case being a carburized pitman arm ball on which the impact was not improved at room temperature but was greatly improved at −60 F.

A malleabilized iron, engine valve rocker arm, which failed on engine tests in 18 to 58 hours when nonpeened, consistently survived 140-hour tests when shot peened.

A spectacular result was obtained in a laboratory tension-compression fatigue test on Allison engine connecting rod bolts where, by cold rolling the threads and shot peening the balance of the bolt, the life under the particular test conditions was increased 16 times.

Oerlikon gun hammers of regular production failed in 8,000 to 30,000 rounds, while those shot peened lasted 20,000 to 40,000 rounds. The average life of several parts for a 20-mm AN-M2 gun were doubled or more by shot peening. In general, the shortest life for the peened part was somewhat greater than the longest life of an unpeened one, but the scatter was wide in both cases.

A recoil spring heat treated to 61-63 Rockwell C failed in about 5,000 cycles. When shot peened, it withstood 400,000 to 700,000 cycles.

Articulated Pratt & Whitney connecting rods, laboratory tested, were compared (1) with rods which had the usual highly polished finish and (2) with rods which were rough polished, then shot peened. At a calculated maximum stress of 90,000 psi, the former ran 80,000 to 100,000 cycles, the latter, 90,000 to 240,000. At 80,000 psi, the former ran 200,000 to 400,000 cycles, the latter, 400,000 to 1,000,000. During the shot peening, the diameter of the 1-in. and 1¼-in. holes in the connecting rods increased by about 1/10,000 to 4/10,000 in. and the 9-in. overall length increased by some 20/10,000, evidence that compressive stress was induced at the surface.

It is argued that this compressive stress provides increased resistance to fatigue failure, since it is tensile stress (tending to open and extend a crack once formed) that produces the damage, whereas, if compressive stress is present, that stress must be released by the applied tensile stress, thereby decreasing the effective tensile stress. It is argued also that it is this compressive stress rather than the strengthening of the surface that confers improved fatigue resistance. The results from some of the case histories demonstrate rather spectacular improvement. In other cases it is a tossup whether any improvement has been effected. In a few cases actual deterioration occurs, as in a case of a final drive pinion carburized and treated to 58-65 Rockwell C. On the other hand, a carburized ring gear at the same hardness was much improved. On torsion bars, surface rolling was equivalent to shot peening.

An enthusiastic "missionary" attitude prevailed throughout the reports, and on the whole this was justified. Specific exceptions bring out the importance of avoiding over-cold work, the existence of scatter, and the necessity of putting the peening operation under close control.

A factor to consider is decarburization, which is extremely damaging in fatigue, this damage not being entirely repairable by peening. In evaluating the benefits of peening, concurrent attention must be paid to decarburization.

One of the useful conclusions to be drawn from the assembled case histories is that some improvement ordinarily is to be expected from the treatment, but there are sufficient exceptions to prevent its being classified as a cure-all. Especially where the life of unpeened parts shows a wide variation, the causes of that scatter are not necessarily overcome by peening, so that there also may be correspondingly wide scatter in the life of the peened parts. Experience with large numbers of tests and evaluation of the data from the probability point of view would be required to appraise such cases accurately.

In July 1944, the Office of the Chief of Ordnance, Army Service Forces, requested NDRC to undertake the preparation of a manual on the shot peening process and its effective application for the guidance of design engineers. This project, OD-177, was not undertaken since there was insufficient time or personnel to carry out the more important phases of the original program and prepare the manual as well. The Research Laboratories Division of General Motors Corporation recognizes the need for such a manual, however, and plans to prepare one when time permits.

Induction Hardening

To augment the studies of surface pre-stressing by shot peening, Project NRC-78, Study of Surface Pre-Stressing on Dynamic Properties of Metals, was established in the research laboratories of the General Electric Company. The aim of the program was to study the effects of flame and induction hardening,

carburizing, nitriding, cyaniding, etc., on the fatigue life of various metal parts of war materiel. Since the progress was not encouraging on the initial phase of the program, which consisted of experimental induction heat treatments on SAE 1050, X1050, and a chromium-molybdenum steel, the project was abandoned. It was indicated, however, that the fatigue endurance limit is increased by 50 per cent and that the origin of fatigue failures in induction-hardened bars is sub-surface. It was found also that induction hardening produces tension in the center of cylinders and compression at the surface. The report on this work was not issued because more comprehensive information of this nature can be found in the technical literature on induction hardening.

1.4.3 Methods of Testing Aircraft Materials

The test methods used by industry for evaluating the various materials used in aircraft construction frequently vary considerably from those used by the testing and procurement agencies of the Army Air Forces and the Bureau of Aeronautics, Navy Department. In order to promote the standardization of these test methods, the NACA Committee on Materials Research Coordination requested the War Metallurgy Committee to review and compile the test methods currently in use at the Materials Laboratory, Engineering Division, ATSC, Wright Field.

Accordingly, Survey Project SP-24 was established and carried out. Twelve NDRC reports were issued covering the test methods used at Wright Field on various aircraft materials, as follows:

- Part I *Test Methods of the Structural and Mechanical Test Branch.*
- Part II *Test Methods of the Metallurgical Branch.*
- Part III *Routine Chemical Analysis Methods of the Physics Branch.*
- Part IV *Test Methods of the Wood and Glue Branch.*
- Part V *Electrochemical Methods of the Chemical Branch.*
- Part VI *Physical Test Methods of the Physics Branch.*
- Part VII *Test Methods of the Welding Branch.*
- Part VIII *Textile, Paper, Leather, and Fungicide Test Methods of the Textile and Rubber Branch.*
- Part IX *Fuel and Lubricant Test Methods of the Chemical Branch.*
- Part X *Paint and Protective Coating Test Methods of the Chemical Branch.*
- Part XI *Rubber Test Methods of the Textile and Rubber Branch.*
- Part XII *Title Index of Parts I to XI, Inclusive.*

These reports are unclassified and were distributed widely throughout the aircraft industry as well as to the Armed Services. In addition, the Materials Laboratory of Wright Field has reduplicated these reports for distribution to suppliers of aircraft materials so that they may utilize in their own testing the methods by which their materials will be evaluated by the Army Air Forces.

1.4.4 Fatigue of Aircraft Structures and Materials

Both laboratory tests and service experience have demonstrated that a structural material will fail after many repetitions of a stress which is substantially less than the stress at which failure occurs under continuously increasing load. Such failure under repeated loading is called failure by fatigue. Since aircraft structures particularly are subject to vibration, impacts, and other repetitive loads, it is reasonable to anticipate the failure of some aircraft parts by fatigue.

Present aircraft structural designs are based upon static load distributions and generally have afforded adequate fatigue strength in primary structures. Prior to 1939, few failures had occurred in which fatigue was a primary cause, and in no instance had it been proved that any airplane wing spar or airship structural girder had failed in service owing to fatigue. Fatigue failures, noted since then, have been very few in proportion to all known aircraft failures.

Nevertheless, present trends in modern airplane design may lead to greater danger of fatigue failure in the near future. Higher speeds, increased wing loading, and in military planes increased fire power and maneuverability tend to produce greater dynamic loading. The use of new materials which have higher static strengths, but which do not have proportionately higher fatigue strengths, increases the possibility of failure of parts by fatigue. Radical

changes in design, as may occur in jet-propelled ships or in rotary-wing aircraft, need to be considered in the light of dynamic loading and possible fatigue failure of parts.

To determine the extent and nature of the available information on the fatigue properties of materials and structures in aircraft so that research needs could be ascertained, the NACA Committee on Materials Research Coordination requested the War Metallurgy Committee to review the published and unpublished information available from aircraft companies, manufacturers, and other laboratories.

To carry out this survey, the War Metallurgy Committee established Survey Project SP-27, Fatigue Properties of Aircraft Materials and Structures. Although there had been many instances of fatigue failures of attachments and fittings which are not structurally important, the study was limited to the primary load-bearing structure of the airframe. Engines and propellers also were omitted because of the considerable amount of readily available information concerning the fatigue properties of their materials and parts.

More than 1,000 references were reviewed from the library of Battelle Memorial Institute, from aircraft manufacturers, and from other laboratories. Of these, about 600 concern the fatigue properties of materials. Fewer useful references were found concerning the fatigue properties of airframe structural elements, repeated-load tests of assemblies, and service loading of aircraft structures.

Part I of the report on this survey[77] summarizes available information concerning the fatigue properties of materials commonly used in airframe construction. This summary is designed to indicate the extent of available information rather than to offer a handbook of design values. For many details, reference is made to available publications.

Part II summarizes the results of fatigue tests on fabricated parts, on simple joints, and on stiffened panels. Although actual stress values usually are not known, the tests are of considerable interest because they include the effects of the stress raisers and surface conditions encountered in production.

Part III describes results of typical tests of structural assemblies under repeated loads. Such tests include an additional factor of importance in service, namely, the deflection characteristics of the structure under the dynamic loading applied.

Part IV of the report discusses the correlation of information from laboratory fatigue tests with information from service records of loading during flight and landings. This discussion does not contain definite conclusions for use in design, but summarizes available information and points out problems for future consideration.

Chapter 2

ARMOR

2.1 INTRODUCTION

Early in 1942 the War Metallurgy Committee initiated several research projects in the metallurgy of armor as a result of the recommendations of the NDRC *ad hoc* Committee on Armor Plate in its report to Dr. James B. Conant, dated November 18, 1941.[78] These projects comprised studies on investigations of the effects of hydrogen, oxygen, and nitrogen in armor plate, the correlation of the metallographic structure of armor plate hardness, and the development of a nonballistic test for determining armor plate quality. At the same time, a comprehensive investigation of fundamental problems in production and heat treatment of armor brought about by the critical shortages of the alloying elements used in armor plate at the beginning of World War II was initiated at the suggestion of Watertown Arsenal. Starting with problems of conservation and substitution, this work included studies of the influence of melting practices on the resultant armor, the effects of various elements on the quench-cracking susceptibility of cast armor, the effects of heat treatments on the properties of homogeneous armor plate, and the development of improved methods for the production of homogeneous armor plate and of face-hardened armor plate. Supplementary projects were established for a more detailed investigation of other problems such as the use of boron as a hardening element, the use of flame hardening, and the development of low-alloy armor compositions. All this work was carried out in close cooperation with Watertown Arsenal and with the Subcommittees on Cast and Rolled Armor, Ferrous Metallurgical Advisory Board, Ordnance Department, the membership of which included many representatives of the various producers of cast and rolled armor, as well as government representatives. Reports on this work were distributed to the members of these subcommittees at the request of the Ordnance Department.

2.2 CORRELATION OF TESTING METHODS

Determining the suitability and acceptability of armor by ballistic testing at the Proving Grounds is an expensive and time-consuming task. The test has been appraised by those in position to know it as "arbitrary and not sufficiently discriminating." If more precise ballistic tests or some simpler method of evaluation could be found whose correlation with actual ballistic tests were definitely and fully established, the development of better armor, the proving of suitability of alternate, alloy-saving compositions, and the prompt acceptance or rejection of armor would be facilitated.

As a result of the recommendations of the NDRC *ad hoc* Committee on Armor Plate,[78] the War Metallurgy Committee established at Carnegie Institute of Technology Project NRC-6 (OD-84), Non-Ballistic Test for Armor Plate. The investigations made on this project established a rough correlation between poor ballistic behavior of rolled homogeneous armor of 1½-in. and 2-in. thickness and either the reduction in area on specimens taken in the thickness direction or the low energy absorption of normal-size notched impact specimens broken at a low temperature. That is, with certain reservations, the conclusion was reached that good ballistic behavior is characteristic of rolled homogeneous armor plate in which the reduction of area in the thickness-tensile test is consistently greater than 30 per cent and the V-notch Charpy values exceed 25 ft-lb at minus 40 C, whereas plates in which the reduction of area in the thickness-direction tensile test falls below 10 per cent and the V-notch Charpy values at minus 40 C are less than 17 ft-lb will be rejected by ballistic tests.[79]

These conclusions are valid only when the failure to pass Specification AXS 488 is caused by cracking or because the exit dimension in the penetration-through-plate test is in excess of the specification limit. Furthermore, they are applicable only when the uniformity of a lot of armor plate has been established by an adequate number of both types of tests. These conclusions do not apply to badly laminated plate for which the properties are known to be widely different at different points, nor to lots of plate which for any other reason are markedly nonuniform.

Some theoretical justification of these conclusions was claimed on the grounds that high impact velocity allows little deformation and in low-tem-

perature tests deformation is likewise restrained.[80] However, consideration immediately brings out a significant lack of similiarity in the two cases, for, when a projectile hits armor, the spot becomes extremely hot, a condition which is lacking in notched-bar tests.

In any event, the assumption of a basic correlation rests on inadequately demonstrated grounds, since cases are on record where armor which the impact test would reject passes ballistic tests and vice versa. Therefore, it must be concluded that a nonballistic test sufficiently discriminating to differentiate the acceptable from the unsatisfactory armor was not developed on this project.

However, the indications are that a 1½-in. or 2-in. plate with less than 10 per cent reduction of area (averages of six specimens) in specimens taken normal to the plate will fail by back spalling, that is, the exit dimension in penetration will exceed the specified limit. Such plate could be rejected without ballistic test. Plate with values of 30 per cent or over will not fail by back spalling and, if there is adequate evidence that such a plate would have proper resistance to penetration, ballistic testing might be omitted, provided that the plate were also resistant to cracking. Cracking is not necessarily prevented by high ductility. Plates with 50 to 60 per cent reduction of area on specimens taken normal to the plate have failed by cracking, while others with 15 per cent reduction of area have been acceptable.

Cracking showed a fair correlation with notched impact behavior. Data from standard Charpy V-notch specimens, taken with the long axis in the width direction of the plate and the notch in the thickness direction and at −40 C indicated that plates with over 25 ft-lb Charpy value will be free from cracking, while those under 17 ft-lb usually are not. There was no correlation between notched bar results and spalling.

It is recognized that the spread in energy absorbed between plates that have been accepted and those that have been rejected is at times small indeed. It is well known that the type of fracture, whether fibrous or brittle, is of quite as much importance in evaluating notched behavior as is the numerical figure of ft-lb of energy absorbed. One important advantage of the notched-bar test using either the small Charpy specimens or the fracture specimen recommended by Army Ordnance is that the type of fracture, whether fibrous or brittle, is readily disclosed.

Various other lines of attack failed to show any correlation between the other mechanical properties and cracking or spalling. Only the two properties mentioned held forth any promise.

It must be recognized that an insufficient number of plates were tested to allow evaluation of the data by probability methods or to justify drawing sweeping conclusions. Further extensive work is necessary to prove a degree of correlation that would justify substitution of tests of either reduction of area in the plate-thickness direction or Charpy notched-bar results for ballistic testing in specifications for acceptable armor plate.

As a supplementary topic of investigation,[79] the size effect in slow bend testing of keyhole-notched bars was studied on one billet of SAE 4140 steel. Rather consistent relations were found between energy absorbed per volume deformed in geometrically similar bars, the unit work to fracture dropping as the size increases from ⅛ in. to 2 in. in width, or as the hardness of quenched and tempered specimens increases from 250 to 450 Vickers.

Although the notched bar fracture test, developed and employed by the Army Ordnance Department, has proved fairly satisfactory as a criterion for rejection for both rolled and cast homogeneous armor, it has the weakness that its value depends so much upon the personal judgment of the inspector that careful training is necessary before readings of the appearance of the fractures by the inspectors are interpreted alike.

There is a belief, based on early observations by von Kármán, that the stress wave resulting from a very high-velocity impact travels in a peculiar fashion so as to build up peaks of extremely high stress. This theory and the experimental work which attempted to evaluate these stresses and their distribution when the impact is produced by other than ballistic means is discussed under the subject of the behavior of metals under dynamic conditions in Section 9.3.2 of this report. The attainable velocities were so low that the questions remained unanswered. Pioneering experiments indicated only how great are the experimental difficulties and failed to advance the situation with respect to armor plate much beyond the original statement of von Kármán. The results of some experiments did not agree very closely with the theory. This served

to emphasize the fact that the simplest way to attain explosive velocity is to use explosives.

Work done by the Navy has indicated interesting possibilities in the use of a test on notched impact bars of the Izod type but larger than the conventional Izod bar, in which the bar is broken by an impact delivered by a bullet instead of by a low-velocity pendulum. The results are reported, not as the foot-pounds of energy absorbed, but as the bullet velocity that is just sufficient to fracture. This brings in higher velocities, although the stress raiser inducing fracture is not that produced by the projectile.

A preliminary method developed for the shock testing of welded armor plate joints by the use of a demolition explosive also showed promise as a nonballistic test for prime homogeneous armor. The work was conducted at Trojan Powder Company on Project NRC-25 (OD-76) (NS-255), Direct Explosion Test for Welded Armor and Ship Plate.[81, 82]

In one of the tests developed, a charge of closely controlled explosive, placed just where the impact is desired, is detonated in contact with the plate. This test detected differences in heat treatment of the armor, in welding technique, or in quality of weld as related to the welding electrode used.[82]

This work included also the development of a point blank test. In testing armor, the impacts of the projectiles must be on or near the weld in order to determine the resistance of the weld to penetration. With current ballistic testing methods, it is often necessary to fire many shots to get an impact in the desired location. Better positioning of impacts would be a boon. With modern methods of measuring projectile velocity, only a few inches of travel are required for a determination. A commercial "gun," which shoots a projectile into a steel plate to a distance regulated by the charge, was designed long ago for embedding studs (for example, to attach a lifting device to the shell of a sunken submarine). With careful selection of the explosive and careful weighing and loading, the distance of penetration is under close control, which means that the velocity is accurately controllable.

Combining these methods, a smooth-bore gun is loaded with a controlled charge which propels a piston to which is attached a projectile. This projectile, for test of relatively thin plate, travels only a few inches, and the point of impact can be determined within 0.1 in. Thus a projectile can be directed at the exact spot it is desired to hit and propelled with an exactly known and measured velocity.

There seems no reason why this method cannot be scaled up for testing heavy plate. The variables that impede ordinary ballistic testing would thus be avoidable and the way opened to secure accurate testing of armor and to obtain data for the correlation of actual ballistic resistance, determined at velocities that meet service conditions, with the results of low-velocity notched-bar impact tests. Haziness of the claimed correlation between low-velocity, low-temperature impact results and ballistic test results is at present ascribed to the deficiencies of the ballistic test. Since with the above-described method the point of impact is under control, the area of the armor plate to be tested can be smaller. Therefore, cooling the armor to subnormal temperatures for evaluation of low-temperature behavior and for direction comparison with low-temperature impact tests becomes more feasible, and a field is opened up which obviously requires intensive tilling.

The direct explosion test is also discussed in Section 6.1.2 of this report in connection with the testing of welded armor and ship plate.

2.3 INVESTIGATIONS ON IMPROVEMENTS IN ARMOR PLATE

The majority of the Division 18 investigations on armor plate had to do with improving the properties of armor plate compositions in existence at the initiation of the program and with seeking to reduce their alloy contents. One of the basic objectives of the work was to save strategic alloying elements at a time when their scarcity made it imperative that the utmost attention be given to the production of high-quality armor steel with a minimum expenditure of alloys. Later, as the scarcity of alloying elements eased, the emphasis was directed toward possible improvements in the general quality of armor through further studies of such variables in heat treatment, structure, composition, and manufacture as are likely to influence the ballistic behavior of armor. While the work in its early stages, exclusively concerned armor under 2 inches in thickness, the protection of much heavier mechanized equipment which developed as the war continued

made it necessary to focus attention on armor in thicknesses up to 6 inches.

The various phases of research with respect to improvements of armor involved both face-hardened and homogeneous types. The work fell within the following three principal divisions:

1. Face-hardened armor.
2. Low-alloy homogeneous armor steel.
3. High-alloy homogeneous armor steel.

2.3.1 Face-Hardened Armor

The regular methods by which armor plate is given a hard penetration-resisting face and a tough, spall-resisting back are by carburizing the face, heat treating for diffusion to secure a desired carbon gradient, then quenching and tempering. These methods are time consuming. Quicker methods and, of course, better armor were eagerly desired. Several projects under the sponsorship of NDRC dealt with face-hardened armor.

Experiments were conducted at the Massachusetts Institute of Technology under Project NRC-23 (OD-88), Determination of the Effects of Flame Hardening on the Ballastic Properties of Pre-Heat-Treated Homogeneous Armor Plate, to study the effects on ballistic properties of flame hardening one face of homogeneous armor of accepted composition and to compare these properties with those obtained on similar thicknesses of carburized plate. Flame hardening was accomplished by heating one face of the plate very rapidly with a very hot flame, thus producing a temperature gradient of such magnitude that, on quenching, a hard surface was obtained, leaving the center and the opposite face of the plate in their original condition. The variables investigated were thickness of plate, depth of hardened layer, the effect of overlap, post-heat treatment, and distortion of plate. A somewhat similar program was carried out by flame softening as quenched fully hardened homogeneous armor in order to obtain a greater depth of hardened metal than was possible by flame hardening.[83]

An improvement in the ballistic limit of ½-in. armor was produced by flame hardening, but warping was excessive. In 1-in. plate there was less distortion and the ballistic resistance against projectiles striking head on was improved, but for oblique impacts it was decreased. A decrease in ballistic resistance was found in 1½-in. plate. It was therefore concluded that flame-hardening ½-in. plate was impractical, that flame-hardened 1-in. plate afforded insufficient overall improvement to warrant its use on combat vehicles, and that flame-hardening 1½-in. plate was injurious.

Flame softening, a practice which consists of tempering with a hot flame the back side of a quench-hardened plate in order to obtain a softer condition on the back than on the front, produced less distortion in ½-in. plate, and the ballistic results approached those of regular ½-in. face-hardened armor. In 1-in. flame-softened plate, there was little distortion, and plates tested with caliber 0.50 AP M2 projectiles at normal impact were as good as the usual carburized face-hardened armor. In 1½-in. plate, it does not appear feasible to soften in this manner a depth sufficient to avoid back spalls.

Thus flame softening appears better than flame hardening. Flame softening may be useful on ½-in. armor if some warping is not objectionable. It appears to have distinct possibilities for 1-in. armor, although the process does not seem applicable to plate much thicker than 1 inch.

Another method of producing hard surface on plate without changing its composition was investigated by the Buick Motor Division of General Motors Corporation on Project NRC-24 (OD-74), The Development of a Process for Manufacturing and Welding Face-Hardened Armor Plate. In this method, two plates placed back to back were welded together around the edges, heated to the quenching temperature, quenched in brine, tempered at 400 F, and then cut apart. Steels were chosen of such hardenability that only the faces of the plates toward the quench were hardened, while the backs remain unhardened. A simultaneous objective of this investigation was to use steel of plain carbon composition in which the hardenability is regulated by raising the manganese content as the plate thickness is increased, and, in order to use as little manganese as possible, to induce hardenability by the use of boron in finishing of the heat, thus conserving critical alloys.

Encouraging results, initially obtained for two small ½-in. plates of 0.40% C, 0.85% Mn, and 0.20% Si boron-treated steel, were the basis for an arrangement to investigate the proposed differential quenching process. Attempts to produce plates of the size required for ballistic testing produced dif-

ficulties and discordant results, neither ½-in. nor 1-in. differentially quenched plate being produced in these larger sizes that passed ballistic requirements. Few approached the requirement as to resistance to penetration, and, in those which did, back spalling was excessive. It was finally concluded that the pearlitic structure of the unhardened back of the plate was inherently unadapted to resist spalling.[84]

The Buick Motor Division on Project NRC-30 (OD-74), Development of Processes for the Manufacturing and Welding of Case-Carburized Armor Plate from Non-Alloy Steels, also investigated a process for case-carburizing armor plate in an effort to develop satisfactory armor with the use of boron-treated plain carbon or low-alloy steels.

In this investigation, gas carburizing with proper control of the carburizing atmosphere was used to produce a lower carbon case than is normally obtained by carburizing with solid carburizers. A wide variety of case depth and modifications in carburizing times and diffusion times were investigated. At the time this research was undertaken, the conservation of critical alloying elements was still highly important, so the use of manganese and boron treatment or of some of the low-alloy National Emergency [NE] steels, whose alloy content is derived chiefly from scrap, were studied. The work was concentrated on light armor. The steels chiefly used were the plain carbon type with 0.16% C, 0.76% Mn, boron-treated, and the NE 94T20 type containing 0.20% C, 1.0% Mn, 0.50% Si, 0.30% Ni, 0.30% Cr, and 0.10% Mo with boron treatment.

The latter steel, gas carburized and then given a diffusion treatment in a neutral atmosphere, had a carbon content of about 1 per cent at the face, with the case depth extending about half the thickness of ⅜-in. plate. Such plate gave ballistic results equivalent to those required for somewhat thicker plate with no spalling. These promising results led to an extension of the work to aircraft armor and ammunition test plate using ¼-, ⅜-, ½-, and ¾-in. thicknesses, the steel chosen being NE 86T17 type (0.17% C, 0.80% Mn, 0.30% Si, 0.15% Ni, 0.50% Cr, 0.20% Mo, boron-treated). After gas carburizing and tempering at 325 F for 2 hours, all the plates showed excellent resistance to penetration but were marginal in shock test.

A series of regular commercial-grade face-hardened armor plate with about 4 per cent nickel and another series of plates of NE 86T17 and 86T20 steel were prepared and sent to Aberdeen Proving Ground for testing at normal and sub-zero temperatures. Both series had plate in the four thicknesses mentioned above with case depths of 25 and 40 per cent of the plate thickness. The results of the room-temperature test indicated that with the NE 86T17 and 86T20 analyses satisfactory resistance to penetration can be obtained, but the general shock and penetration-through-plate characteristics were either borderline or definitely below the requirements of Specification ANOS-2. The low-temperature test brought about a very marked decrease in the shock properties of this armor with plates failing to meet ballistic requirements by more than 700 fps.

On the other hand, regular commercial-grade face-hardened armor gave excellent shock and penetration through plate results at both normal and sub-zero temperatures. Their resistance to penetration also was fairly high for this steel.

It appears that the NE 86T17 and NE 86T20 steels are not suitable for processing armor under Specification ANOS-2 using the treatment employed.[85,86]

In somewhat analogous fashion, work was conducted at Battelle Memorial Institute aimed at increasing the toughness of the case on face-hardened armor by holding down the surface carbon in ordinary pack carburizing.[87] This work was part of Project NRC-14 (OD-87), Improvement of Low-Alloy Armor Steels. Some earlier work suggested that additions of ferrosilicon to the carburizing compound would result in lower surface carbon in the case. In tests of this on armor steels, erratic results were obtained, and it appeared that the ferrosilicon was acting as a diluent just as so much magnesia or silica flour does. However, when both ferrosilicon or silicon carbide and certain chlorides, especially nickel chloride or chromium chloride, were added, a reduction in surface carbon was obtained. The chlorides alone were energizers, and in 8 hours at 1700 F carburizing without the silicon compound they produced surface carbon contents of 1 to 1.10 per cent. With the silicon compound, the surface carbon could be held down to 0.45 to 0.90 per cent carbon as desired.

In effect, this process eliminates the need for a diffusion treatment to lower the maximum carbon content of the case after the carburizing cycle. Since appreciable lowering of the carbon content can be

accomplished without reducing the hardness of the case, it is thus conceivable that the ductility and toughness of the case could be decidedly improved without any sacrifice of ballistic properties. No ballistic tests were carried out, however, on plates so carburized.

2.3.2 Low-Alloy Homogeneous Armor Steel

As part of Project NRC-14, Improvement of Low-Alloy Armor Steels, the literature and patents were surveyed for information regarding the use of small additions of various elements or alloys to improve certain qualities of steel. The object of this survey was to determine whether or not any of these materials could be used to improve the ballistic properties of the armor steels or to reduce their alloy content with no reduction in ballistic properties. As a result of this survey, a large number of tests were made of various additions. A list of these addition agents includes boron, aluminum, silicon, tellurium, calcium, selenium, titanium, columbian, lithium, zirconium, nitrogen, and a number of proprietary alloy additions of complex analyses.[88,89,90,91]

Outside of the boron addition, none of the treatments were outstanding in their effects, although several of them contributed minor improvements. Zirconium, for instance, gave a definite boost to the depth hardening properties, although it seemed to decrease the notched bar toughness. On the basis of these preliminary tests, it was decided to discontinue further study on all other treatments and to concentrate on an investigation of boron in armor steels.

Investigation of Boron in Armor Plate

The amount of boron required to increase materially the hardenability of an already somewhat hardenable steel is almost unbelievably small. The proper amount to add is considered never to be over 0.007 per cent. Peacetime commercial experience with boron steels was sufficient to justify much hope but too meager to supply all of the answers to the questions that must be answered before the boron-treated steels could be adopted for armor. Not all attempts to confer hardenability by boron treatment were successful. The mechanism by which boron confers hardenability is not understood, and, while the conventional metallurgical tests for mechanical properties had been made on many boron-treated steels that were mechanically equivalent to more highly alloyed steels without the treatment, there was little experience with them in various types of severe service, and none at all in armor. The various unknowns in respect to boron-treated steels, therefore, became the basis for investigations to determine the actual possibilities and limitations of these steels in order to establish confidence in their use. The problems directly related to armor were of great interest to the Army Ordnance Department, and several projects were set up to bring out the unknown facts.

A study of the influence of boron on some of the properties of experimental and commercial steels was carried out at the National Bureau of Standards under Project NRC-31 (OD-87), Investigation of Boron in Armor Plate. The results of this investigation are summarized in a series of progress reports covering a period of two years of work on the following subjects:

1. Influence of variations in boron, carbon, and manganese contents on some properties of steels for armor plate and other military applications.[92]
2. Influence of variations in boron, carbon, and manganese contents on the weldability of steel for armor plate and other military applications.[93]
3. Influence of nitrogen on some properties of steels with and without boron and titanium additions.[94]
4. Influence of variations in boron, composition of ferro-alloys used for making boron additions and deoxidation practice on some properties of experimental steels containing 0.3% carbon and 1.6% manganese.[95]
5. Influence of boron and nickel on some properties of experimental steels containing 0.3% carbon and 0.8% manganese.[96]
6. Influence of boron and chromium on some properties of experimental steels containing 0.3% carbon and 0.8%, 1.25%, or 1.6% manganese.[97]
7. Influence of nitrogen on some properties of experimental steels without and with boron.[98]
8. Influence of boron on some properties of experimental steels containing nickel and chromium.[99]
9. Influence of variations in boron and composition of ferro-alloys used for making boron additions on some properties of basic open-hearth steels containing 0.4% carbon and 1.6% manganese.[100]

The final report on this project covered an in-

vestigation of boron in armor plate dealing with the influence of boron on some properties of experimental steels containing 0.3% carbon and varying amounts of manganese, chromium, and molybdenum.[101]

Tests were made on approximately 250 experimental and 20 commercial steels. All of the experimental steels were prepared at Battelle Memorial Institute on Project NRC-31A. In the work at the National Bureau of Standards it was shown that variations from nil to 0.006 per cent boron additions made with intensifiers either with or without grain refining elements had no significant influence on the following properties of the steels: (1) cleanliness, (2) hot working, (3) transformation temperatures, (4) resistance to softening by tempering, and (5) tensile strength when the steels were fully hardened and tempered, except possibly in improvement in ductility when tempered at low temperatures. Although boron lowered the coarsening temperature of austenite, steels with relatively high additions of boron could be rendered fine grained at heat-treating temperatures by the judicious use of grain-growth inhibitors such as aluminum, titanium, zirconium, and vanadium. It was shown that the influence of boron on hardenability and notch toughness varied with the base composition of the steels, the composition of the intensifiers, and the amount of boron present. Small amounts of boron were often beneficial to notch toughness at room temperature when the steels were fully hardened and tempered at low temperatures. When tempered at high temperatures, however, the presence of boron in steel, especially when added in relatively high amounts as intensifiers containing titanium, was usually either without effect or was detrimental to notch toughness at room and sub-zero temperatures.

The hardenability of many of the experimental steels prepared in an induction furnace and of all the steels comprising a basic open-hearth heat was markedly improved by additions of boron. However, no definite correlation was found between the hardenability effect and the amount of boron added or retained in the steels. In many of the experimental steels, the optimum hardenability was obtained with small additions of boron (0.001 per cent or less), while in other steels the hardenability increased continuously with increasing boron content. In still other steels, the addition of boron, either as a simple or as a complex ferro-alloy or intensifier, was without effect on hardenability. In general, relatively small additions were more effective than large. The complex intensifiers were more effective than the simple ones, and the improvement in hardenability was not so critically dependent upon the amount present when the additions were made with a complex intensifier.

The effectiveness of boron in improving the hardenability of the experimental steels increased with increased amounts of elements that conferred deep hardening properties, such as manganese, chromium, and molybdenum.

A progress report on the endurance properties of basic open-hearth steel containing 0.4% carbon and 1.6% manganese without and with boron additions contains the results of additional work done at Battelle Memorial Institute on Project NRC-31A. This report[102] covers the endurance properties of three steels from the special commercial addition agent Heat No. 126405, Army Research and Development No. R.A.D.-1448. Two of the steels were treated in the mold with proprietary boron-containing alloys, while the third was a reference steel from the same heat containing no boron. This work was designed to supplement that conducted at the National Bureau of Standards on physical properties of steels from the same heat which was summarized in a progress report cited earlier.[100] The endurance properties of boron-treated steel were comparable to those of the reference steel when tempered to the same hardness value, thus indicating that boron had no measurable effect on the endurance properties.

Further information on boron is contained in a War Metallurgy Committee advisory report entitled *Boron in Steel*.[103] This report is a very interesting presentation of the state of the knowledge in this field in 1942. It contains a comprehensive statement of the history of the use and effect of boron in steel.

A final report on the improvement in low alloy armor steels dealing with boron in steel of armor composition,[104] contains also the results of an investigation of boron as an alloy in steel. The investigation was part of the program of Project NRC-14 (OD-87) and covered the use of boron in armor steel but more specifically its use as a substitute for molybdenum. About the time the work got under way, the use of molybdenum was drastically restricted, and it seemed appropriate, in view of the probability of a continued shortage, to limit the investigation of boron as an alloy to its possible use as a substitute for molybdenum. The results show that boron can be substituted for a much larger quan-

tity of molybdenum as far as hardenability goes, but it does not have the specific effect of molybdenum in mitigating temper brittleness. It does not lower the critical temperature and the quenching temperature as nickel does, but that is not very important. On the whole, amounts of nickel, molybdenum, and chromium well worth saving can be replaced by a tiny amount of boron on the basis of mechanical test results.

The presumption is, therefore, that the much desired avoidance of slack quenching in the interior of relative heavy armor can be achieved by boron treatment up to thicknesses that would require excessive amounts of the usual alloying elements. Depending somewhat upon the quenching technique, there is, of course, a maximum thickness beyond which no combination of elements, whether or not assisted by boron, can achieve avoidance of slack quenching, and structures less desirable than tempered martensite have to be put up with. How useful boron may be in very heavy armor that cannot be given any but a slack quench structure remains to be evaluated.

The use of boron in steels suitable for 3- to 6-in. cast armor was also investigated.[105] A fairly comprehensive testing program was conducted on material cast into 6-in. plate to investigate the use of boron in steels of armor composition and to determine the effects of variations in deoxidation treatment on the boron effect. Boron did enhance the hardenability of these steels without increasing their susceptibility to quench cracking or to temper brittleness, and, so far as could be determined, conferred no undesirable characteristics. A deoxidation treatment with aluminum seemed to give consistent and better results than were obtained when titanium was used prior to the boron addition.

The studies of the use of boron for reducing the alloying elements in armor steel without sacrificing ballistic properties bore out the fact that armor with relatively low alloy content but with the boron treatment would be equivalent to armor richer in alloy content.

An inquiry to Watertown Arsenal brought out the fact that boron additions used by some producers had not been consistently reported, but that in so far as segregation can be made, ½-in. and 1½-in. rolled homogeneous armor steels with higher molybdenum and no boron and those with lower molybdenum and a boron addition are indistinguishable in ballistic tests. Some producers of rolled armor made effective voluntary use of boron to insure hardenability in alloy-poor compositions that would otherwise be on the borderline of hardenability. With the information now available, a much greater saving of alloy than was actually accomplished would now be feasible. Producers of cast armor do not seem to have made much use of boron, as their understanding of its use seems, in general, to be less than is the case with steel mills.

As a further step toward conserving strategic alloying elements by employing boron in alloy-free or low-alloy steels, the Buick Motor Division of General Motors Corporation carried out Project NRC-29, Development of Processes for the Manufacturing and Welding of Homogeneous Armor Plate from Non-Alloy Steels. The basic idea again was the saving of strategic alloying elements by using alloy-free or low-alloy steels whose hardenability had been augmented by boron treatment. The project dealt with homogeneous plate from ¼ in. to 1 in. thick, both in the machinable and high-hardness grade.[106,107]

Using steel of about 0.27% carbon, 1.15% manganese, plus an addition of boron, it was found possible to produce ½-in. plate with satisfactory ballistic performance, but it was difficult to secure both resistance to penetration and freedom from spalling. Commercial variations in hardenability made it doubtful if uniformly high quality could be readily maintained in production. Attention was, therefore, shifted to steel with a greater margin of hardenability, such as steel with 0.45% carbon, 1.5% manganese, which was boron treated. Satisfactory ½-in. and ¾-in. plates were produced from this steel, but a higher resistance to penetration would have been desirable. When the scrap situation became favorable for making the triple alloy type of National Emergency steel, attention was centered on the NE 9430 type without and with boron treatment. The non-boron-treated NE 9430 steel gave satisfactory ½-in. plate, and the boron-treated steel of the same type gave satisfactory 1-in. plate. These steels were later put into production.

Investigations on the Effects of Gaseous Elements in Armor Plate

Although it is known that the common gases, nitrogen and hydrogen, may have a material effect on the quality of steel, analysis for these elements is seldom made because of difficulties involved in the analytical method. In armor plate, where every

means of improving quality is of paramount importance, the role played by the gases becomes of special interest. Obviously, any information leading to a greater appreciation of the importance of oxygen, nitrogen, and hydrogen would ultimately lead to better armor.[108] This problem was recommended for study by the NDRC *ad hoc* Committee on Armor Plate.[78] Therefore in Project NRC-4 (OD-38-2), Effects of Hydrogen, Nitrogen and Oxygen in Armor Plate, established at Battelle Memorial Institute, it was planned to make a study of these gases from the standpoint of their influence upon ballistic properties. One of the methods used to attack this problem was to carry out direct analyses of armor plate samples in an effort to obtain some correlation between the gas content and ballistic properties. A considerable number of fractional vacuum fusion analyses were made on rolled and cast commercial armor plate representing ballistically satisfactory and unsatisfactory material.[109] Neither hydrogen nor nitrogen values could be correlated with ballistic properties. It was found that rolled plate which failed because of back spalling tended to have higher oxygen content than satisfactory plate. In cast steels, the oxygen content was found to be roughly related to inclusion type. Cast plates of low oxygen content generally contained duplex sulphides. When the oxygen content was relatively high, the inclusions were globular silicates and sulphides. The network or eutectic-type inclusions which lead to inferior ductility, low notch toughness, and generally poor ballistic properties prevailed when intermediate oxygen contents were encountered. Residual aluminum contents were found to vary inversely with the total oxygen values as would be expected from the nature of the nonmetallic inclusions.

In early studies on this project, a peculiar intercrystalline type of fracture was observed in several samples of commercial cast armor. It was noted that the elongation and reduction of area values of steel exhibiting this type of fracture were abnormally low, which is tantamount to saying that the steel had poor ballistic properties. The contour of a fracture suggested that the failure occurred through regions that were originally the primary austenite grain boundaries. Careful examination of a sample under the microscope revealed the presence of a chain of nonmetallic particles which were extremely small in size and became apparent only at magnification of 1,000 diameters or more. The aluminum content of the steel was noted to be somewhat greater than normally found where aluminum is used simply for the purpose of deoxidation. Furthermore, analyses showed that the steel contained a higher than normal nitrogen content. Experiments were undertaken which gave conclusive evidence that the presence of aluminum nitride was the cause of the intergranular precipitate in the samples of commercial armor examined.[110] The amount of the intergranular precipitate found in the steel increased with the amount of aluminum used for deoxidation, with the nitrogen content of the melt, and with a decrease in the cooling rate following casting.

As the experimental work on improvement in armor proceeded, additional examples of intergranular fractures were received from various producers of armor plate, and, upon their examination, it became apparent that a number of different conditions could cause such fractures. Various causes of intergranular fracture met with on Project NRC-14 are presented in a report on the causes of intergranular fracture in cast armor plate. The following causes are now recognized: (1) aluminum nitride precipitation at the primary grain boundaries, (2) ferrite precipitation as a network at the primary grain boundaries, (3) massive carbides in the primary grain boundaries, (4) extreme cases of Type II sulphide inclusions, and (5) internal hot tears. Of these, the prime cause was found to be aluminum nitride precipitation at the primary austenite grain boundaries. The information found in these investigations was used in overcoming intergranular fracture problems in a number of foundries producing cast armor.

Investigations of Structure in Homogeneous Armor

During the early periods of World War II, questions arose as to the effect on ballistic properties of the various structural constituents formed during the quenching of armor plate. Investigations soon showed that the effectiveness of the quench was all important. Examination of a large number of specimens of commercial armor plate revealed that some producers did not always obtain full hardening, with the result that some ferrite, pearlite, or bainite, or combinations of these constituents were present after the quench. At the recommendation of the NDRC *ad hoc* Armor Plate Committee[78] a study

was undertaken at Battelle Memorial Institute with the intention of determining the effects of microstructure on the ballistic limit and shock resistance of armor plate. This work constituted the program for Project NRC-5 (OD-83), Correlation of Metallographic Structures and Hardness Limit in Armor Plate. The final reports on this project covered the effects of austenite transformation products on ballistic properties,[112] the correlation of microstructure and ballistic properties,[113] and analyses of problems presented by individual producers.[113]

In a study of the effects of austenite transformation products on ballistic properties, ½-in. rolled armor from a single heat was received and was given the three general types of heat treatment: (1) full quench followed by tempering to the desired hardness, (2) intercritical quench followed by tempering to the desired hardness, and (3) subcritical quench in molten lead. After heat treatment, the plates were sent to Watertown Arsenal for ballistic testing and were then returned for physical testing and metallographical examination. While, for a given hardness, ferrite was shown to have no effect on the ballistic limit, it lowers the resistance to back spalling and causes back spalling to occur at a low hardness value. Plates which were isothermally treated to produce bainite and a small amount of uniform network of ferrite have higher ballistic limits for a given hardness than fully quenched and tempered plate. The fact that isothermal quenching of armor has a serious limitation in that it can be applied at the present time only to thin plate is discouraging to any attempt to develop isothermally transformed armor plate commercially.

In connection with the correlation of microstructure and ballistic properties, metallographic specimens from a large number of cast and rolled ballistic test plates ranging from 1 to 2 in. in thickness were carefully examined from surface to core to note the character of the matrix structure and the inclusions. Examples of both acceptable and unacceptable plates were represented. This investigation disclosed that failure by cracking occurs most frequently in plates having excessive amounts of free ferrite or excessive hardness, but that cracking failures are reduced when the ferrite is fortified by such ferrite strengtheners as copper or silicon. Hardenability data indicated that poor quenching technique is an important factor in the appearance of free ferrite.

In addition to excessive ferrite, nonhomogeneous microstructure and excessive amounts of porosity or nonmetallic inclusions were shown to be undesirable and detrimental to ballistic properties.

Attempts to produce, by controlled heat treatment, various types of metallographic structures in plates substantiated evidence that, for ease of manipulation and best results, a full quench followed by tempering to the desired hardness gave the best type of microstructure for resistance to ballistic penetration and shock.

In examining a limited number of spalled and cracked plates of rolled armor, it was observed that the spalled plates contained much larger oxide inclusions than either the cracked or satisfactory plates, while banding also was found in many of the spalled plates. On the other hand, cracked plates showed a much greater drop in notched-bar toughness when the testing temperature was lowered from room temperature to −40 F than did either the spalled or satisfactory plates. The cracked plates contained much more ferrite at the core and were softer at the core than the satisfactory plate, whereas the spalled plates held a position intermediate to the satisfactory and cracked plates with respect to hardness and ferrite contents of the core.

Inasmuch as proper microstructure is a requisite for good armor plate, the extent to which heat treating variables affect the microstructure and mechanical properties of low-alloy armor steel was investigated under Project NRC-14 (OD-87), Improvements of Low-Alloy Armor Steels.

The purpose of the study was to determine the importance of heating rate, holding temperature, and holding time prior to the quench, and cooling rate during the quench on the microstructure and properties of 2-in. cast armor. Variations in heating rates, holding time, and holding temperature were found to be of little consequence in regard to austenitizing the steels and getting uniformity of temperature through the cross section, provided the holding temperature was above the Ac_3 temperature for the composition. Undesirable microstructures appeared more likely to form as the result of improper handling in the quench.

Tensile test bars that were heat treated to produce 100 per cent martensite in the quenched structure as well as being heat treated to other types of structure indicated that the best combination of strength and ductility is obtained in those bars con-

sisting of 100 per cent martensite. Any variation of this structure resulted in lower ductility with the decrease in ductility being proportional to the amount of ferrite present in the microstructure. Increasing the holding time and holding temperature was found to be beneficial in the case of steels containing carbides which inherently are difficult to dissolve in austenite.[114]

Heat Treatment and Mechanical Properties of Low-Alloy Homogeneous Armor

It was common practice to homogenize the heterogeneous coarse-grained structure developed during the solidification of homogeneous cast armor on the assumption that the treatment refined the grain, diffused segregated areas resulting from the dendritic mode of freezing, and improved the mechanical properties, particularly ductility and toughness. The homogenizing heat treatment is generally carried out at temperatures considerably higher than those used for normal heat treating practice, but there was no consistency among producers of cast armor in regard to either the temperature or the holding time at temperature used. It was not unusual to find one steel foundry homogenizing at 1700 F for 4 hours and another at 2000 F for 10 hours for castings of the same section size. The implication derived from this decided lack of uniformity in homogenizing heat treating practice was that there is no unanimity of opinion in the cast steel industry regarding the value of homogenizing. If it were true that a drastic heat treatment of many hours at high temperature is necessary, then those who employed lower temperatures and shorter holding times were not realizing the maximum properties from their armor. On the other hand, if there were no particular advantage in going to higher temperatures and longer holding times, or if the advantage was so slight that a minor adjustment in composition would compensate for it, then the drastic heat treatment could be curtailed in order to save time and heat treating capacity.

When the immediate importance of this problem to the cast armor producers was recognized, an extensive survey of the homogenizing heat treatment was undertaken at Battelle Memorial Institute as part of Project NRC-14 in order to obtain a better understanding of the value of homogenization and to accumulate data that would be useful to the cast steel producers in governing their heat treating practice. Cast armor plates submitted by five producers were examined carefully after being given various homogenizing heat treatments.

No significant effects or trends from the homogenizing treatment were observed on the austenitic grain size, hardenability, notched bar toughness, or V-notched Charpy at room and subatmospheric temperatures, temper brittleness susceptibility, or tensile properties. The properties of unhomogenized specimens were generally equivalent to those from homogenized material. Successive increases in homogenizing temperature or holding time brought about a gradual diffusion of the dendritic pattern on etched macrospecimens. However, even the most drastric heat treatment did not obliterate this structure. It was generally concluded that, in the steels examined, the various homogenizing treatments produced no appreciable change in the characteristics of the hardened and tempered specimens and that true homogenization can be effected only by holding the steels at temperature in excess of 2200 F.

On the other hand, work described in a report on the causes of quench cracking in cast armor steel[115] showed that a decrease in quench-crack susceptibility accompanied the substitution of homogenizing pretreatment for a normalizing treatment. A homogenizing treatment of 8 hours at 2300 F was particularly effective in decreasing the quench-crack susceptibility.

In line with the investigation of quench cracking in cast armor steel, a test was developed for measuring the quench-crack susceptibility of fully hardened cast armor plate. Quench-crack susceptibility as measured by the test was influenced greatly by the composition of the armor. Steels with less than 0.25 per cent carbon seemed not to be immune to quench cracking, but quench-crack susceptibility increased rapidly as the carbon content increased from 0.25 to 0.35 per cent. Quench-crack susceptibility also increased with increasing nickel, chromium, manganese, and phosphorus contents, but no effects were observed for variations in silicon, sulphur, molybdenum, or boron contents, or in the percentage of added aluminum. On the other hand, increases in the time at the austenitizing temperature and a decrease in the quenching temperature reduced the quench-crack susceptibility.

Two possible factors influencing quench-crack susceptibility of steels are the temperatures at which martensite is formed and the amount of expansion

involved in the transformation to martensite. To investigate this point, an attempt was made to develop a dilatometer which would be sufficiently fast and sensitive enough to show the temperature and expansion of the martensite transformation. This investigation was part of Project NRC-14, and the results are described in two reports on the determination of martensite transformation points[116] and the continuation of dilatometric studies of armor with respect to quench cracking.[117]

For this work, a high-speed dilatometer, using strain gages to register dilation, was designed and built. Difficulties with the drift of the zero point of the instrument and difficulties encountered with a switching device in the electrical circuit were obstacles to the satisfactory performance of the instrument. Martensite transformation points, however, were determined for a number of steels from cooling curves obtained with part of the dilatometer apparatus.

In the production of the cast armor, it was recognized that variations in physical properties of steel are associated with melting and deoxidation practice as well as with variations in heat treatment. Since no universal melting practice is employed among the foundries manufacturing cast armor, and since a number of foundries unacquainted with its production were encouraged to enter the field without adequate knowledge of the problems involved, investigations were undertaken under Project NRC-14 to assist the uninformed foundries by investigating some of the variables in melting practice which have an effect on the quality of cast armor. Several types of melting practice were examined in both acid-lined and basic-lined electric furnaces. The sulphur content itself or the sulphide distribution appeared to be the principal variable controlled by the melting operation which affected the physical and notched bar properties of the steel. When the sulphur content increased or the sulphide inclusions were distributed along grain boundaries, the toughness decreased as it did also with increased amounts of inclusions and in the presence of the aluminum-nitride precipitate. As a general rule, acid cast steels were inferior in properties to basic steels, though much of the difference probably resulted from the higher sulphur content in the acid steels. The hardenability of the steels examined was found to vary over a greater range than could be accounted for by their chemistry. On the average, cast steels were at lower hardenability than wrought steels of the same analyses.[118]

The relationships between chemical composition, mechanical properties, tempering characteristics, and hardenability of cast steels of armor compositions was investigated by the American Brake Shoe Company under Correlation Project NRC-83A, Hardenability of Cast Steels for Use in Ordnance Materiel. This project was financed by the company and carried out under the general supervision of the War Metallurgy Committee. The depth-hardening characteristics of the cast steels were determined, employing single and double end-quench tests to show the effect on hardenability of several alloying elements in several base compositions. It was pointed out, however, that other variables beside compositional changes may effect inherent hardenability. In castings, for example, it was evident that the cast section size may exert considerable influence. Melting and deoxidation practices also were considered significant, while segregation was recognized as a variable of particular importance.

For all practical purposes, the data confirmed the hypothesis that different alloy combinations had little effect upon the usual mechanical properties of fully hardened and tempered cast steels. There was some indication that over alloying, as represented by greater hardenability than needed for full hardening, may result in a slight impairment in properties, particularly by lowering the reduction of area. The influence of several alloying elements upon resistance to tempering also was examined in this investigation. As would be expected, the increased resistance to softening, evidenced by the higher temperature required to temper to a known Brinell hardness value, was associated with steels containing the strong carbide-forming elements, chromium and molybdenum.[119]

Producers of armor plate exercise a certain amount of choice in deciding the tempering time and tempering temperature to be used in meeting a hardness specification. The fact that different producers do make use of different practices in obtaining the same hardness in armor plate led to the question of whether any advantage in mechanical properties could be assigned to a particular tempering practice. Other questions arose as to effect on the mechanical properties, particularly notched bar strength and temper brittleness, of replacing molybdenum with boron. An investigation was un-

dertaken, therefore, as part of Project NRC-14, Improvement of Low-Alloy Armor Steels, to study the effect of tempering practice on mechanical properties of a number of low-alloy armor plate compositions. The steels tested were fully hardened and then tempered to within the range of about 200 to 400 Brinell. The results are contained in one of the final reports. It was shown that tempering practice involving either time, temperature, or cooling rate after tempering does not effect either tensile strength, yield point, elongation, or reduction of area, except in so far as the tempering practice simultaneously affects the Brinell hardness.[120] An excellent correlation was observed between Brinell hardness and either tensile strength, yield point, or elongation, and a less pronounced though still good correlation was found to exist between Brinell hardness and reduction of area.

Tempering practice had, however, a very definite effect on the V-notch Charpy values of those steels subject to temper brittleness. Short draw times followed by water quenching produced the best Charpy values in steels subject to temper brittleness. The Charpy values obtained for steels not subject to temper brittleness, that is, steels containing 0.40 per cent molybdenum, were observed to correlate with Brinell hardness almost as well as did the tensile strength.

Armor steel must retain a large percentage of toughness at sub-zero temperature. While the quality of the steel and the heat treatment employed are known to have a large effect on this property, the alloy content of the steel must also be considered. Nickel, for instance, has been advocated as a desirable element for promoting low-temperature toughness, particularly if used in amounts exceeding 1½ per cent. Because some of the armor plate compositions currently used during the war did not contain nickel as one of the specified elements but often contained appreciable quantities of residual nickel brought in through melting scrap, consideration was given to the possibility of making good use of this residual nickel by adjusting its amount within a composition range that might contribute to the properties of the steel. The possibilities for obtaining some slight gain in the low-temperature toughness by employing nickel in such armor compositions that normally do not contain nickel constituted part of the program.

While quantities of nickel up to 1 per cent were employed in the manganese-molybdenum and the manganese-chromium-molybdenum low-alloy armor compositions in this investigation, no significant change in the toughness of these steels at low temperature as a result of the presence of nickel was found.[121]

2.3.3 High-Alloy Homogeneous Armor Steel

The attainment of a martensitic structure is not difficult normally provided sufficient alloy can be used, but because of past scarcities as well as for production and metallurgical reasons, the goal of 100 per cent martensite after the quench has not always been an easy one to reach. In the early stages of armor plate research during the war, the lack of alloys and the restriction of the carbon content to a maximum of about 0.30 per cent to avoid quench cracks and welding failures required that the steel be handled skillfully to obtain full hardening with the chosen composition. Alloys could not be used promiscuously, and compositions assigned to the heaviest sections were too rich for use in lighter parts. In many ways though, the metallurgical problems were straightforward, for, if the alloy requirements of a plate of one size were known, it was not difficult to make use of a hardenability test and a knowledge of cooling rate to ascertain the alloy requirements for a plate of another size. In terms of the isothermal transformation curves, the nose of the S-curve would have to be displaced one way or another to assure adequate hardenability with minimum alloy content for the section concerned.

These considerations were applicable to relatively light armor plate up to 2 inches in thickness. The fact that an analogous situation does not exist with armor plate of heavier sections is a basis of much research work covered during the latter part of World War II. Many complicating factors prevent the study of heavy armor plate from being similar in kind to that of the lighter sections. First of all, the cooling rates in the heavy sections are below the range of those considered heretofore for quench material. Consequently, it was necessary to determine what these rates were. This was done by extrapolation of experimental results on sections ranging from 3 to 6 inches and by calculations making use of published tables on cooling rates in plates. A progress report on Project NRC-14, Improvement of Low-Alloy Armor Steels, summarizes the experi-

mental work on heavy armor steels and records the experimental and calculated cooling rates at 700 F, 1000 F, and 1300 F for plate thicknesses up to 10 inches.[122] Details are given in an earlier report on the heating and cooling rates of heavy armor plate and the calibration of an air-cooled hardenability specimen.[123]

A somewhat analogous investigation was conducted at the Research Laboratories Division, General Motors Corporation, to determine accurate cooling rates at 1300 F between center and surface of various size rounds and plates when heated under different conditions of temperature and atmosphere and quenched in different media at various velocities. The object of this investigation was to obtain a more accurate correlation of cooling rates of rounds and plates with those of the standard end-quench hardenability bar. While this project was not directed specifically toward armor plate research, nevertheless the field covered was of direct value in interpreting the effect of the massiveness of the section involved in the heat treatment of heavy armor plate. This work was conducted on Project NRC-55, Heat Treatment of National Emergency Steels for Use in Tanks, Combat Cars, Gun Mounts and Other Ordnance Matériel. The progress reports on this project contain a description of the scope of the project, the procedure, and equipment used,[124] a discussion of the cooling curve recorder with sample curves and the methods for analyzing sample curves and the methods for analyzing the the data,[125] and the cooling rates and cooling times in end-quench hardenability test bars of four steel compositions.[126] The final report[127] summarizes all of the data on the project and contains cooling rates and cooling times for water-quenched rounds up to 4 inches in diameter and for 3-in. plate specimens of NE 9445 steel. This project is also discussed in Section 9.4.5 of this report.

In the production of heavy armor plate, 4 in. in thickness and greater, a knowledge of the hardenability required to produce full hardening at the center of such massive plates was desirable. A special type of hardenability specimen having a range in cooling rate below those of an end-quenched bar was developed[123] as part of the program of Project NRC-14.

The cooling rate at 1300 F obtained with the special hardenability bar ranged from about 5 to 1 degree F per second. The utility of this air-cooled hardenability test bar was not so great as originally anticipated because, when testing 20 steels of heavy armor composition, not one changed by more than 2 points Rockwell C between the slow- and fast-cooled end, and only one steel exhibited a conspicuous change in microstructure within the length of this special hardenability bar.

In heavy armor sections, the cooling rate on quenching at the center of the section is much slower than that of the slowest cooling location on the standard end-quench hardenability specimens, and the amounts of dislocation of the isothermal S-curve produced by continuous cooling is unknown and unpredictable. An attempt was made to develop a more rational relationship between transformation during cooling and transformation at constant temperature. The results were intended to make possible predictions of the microstructure present at the center of heavy armor plate by using the isothermal transformation diagram of several proposed heavy armor plate analyses and by using the cooling data on heavy plate.

In the investigation, five 0.3 per cent carbon alloy steels of various chromium contents were used.[128] Cooling was first closely approximated by constant cooling. With this treatment, it was found that from the Ae_3 temperature down to about 1130 F the time spent at a given temperature divided by the time required for beginning isothermal transformation at that temperature may be regarded as a fraction of the nucleation period, and that when the sum of such fractions is equal to 1, nucleation begins. Temperatures from about 1130 F to the Ms temperature constitute a distinct range that is not additive with the higher range mentioned. These findings were used as a basis of a mathematical expression which permit calculation of the temperature at which transformation begins during cooling. In checking the validity of the mathematical expression by use of an end-quench bar, for which accurate cooling curves were available, it was found that the experimental data and calculated data differed appreciably for two of the five steels.

While the discrepancies that occurred between the experimental data and the calculated data can not be properly explained at present, there was some suggestion that stress may play a highly important role in beginning transformation. If stress is capable of affecting the decomposition of austenite to bainite, ferrite, or pearlite, the subject becomes of con-

siderable practical interest since present-day use of isothermal transformation curves and end-quench hardenability data do not consider stress as a transformation variable. The effect of stress and strain on the isothermal transformation of austenite, therefore, became part of the research program. Under certain special conditions, stress and/or strain was shown to be capable of affecting the decomposition of austenite to ferrite, pearlite, or bainite.[129]

Because the tests indicated that, at least under certain special conditions, stress or strain can materially affect the kinetics of the austenite decomposition, the question arose as to whether the stresses or strains which developed during the quenching of commercial parts are sufficient to affect transformation. While the data in this study could not shed any light on this practical problem, further consideration was given to the problem in a study of the correlation between the hardness and structure predicted on the basis of end-quench tests and the hardness and structure actually obtained in various sized rounds and plates. This investigation also was part of Project NRC-14.

In this work, plates and rounds of three different steels 1 to 4 in. in thickness were water quenched, after which hardness traverses and metallographic examinations of the specimens were made and the results compared with those obtained from end-quenched hardenability bars taken from the same heat. These hardness and metallographic comparisons were in turn compared with the relationship between cooling rates in the end-quenched hardenability bar and cooling rates within the various plates and rounds previously determined on Project NRC-55 mentioned earlier. The results indicate that, at the present time, it is not practical to attempt to predict either the hardness or microstructure that will be obtained in rounds and plates on the basis of equal cooling rates. In other words, a point on the end-quench hardenability bar having a cooling rate very similar to a particular position within some plate or round will not necessarily exhibit either the same hardness or the same microstructure found at the corresponding location in the plate or round. Evidently, factors other than cooling rate are capable of appreciably affecting the transformation characteristics of the steel. One of these factors may be stress.[130]

One of the subjects investigated was the metallurgy and properties of armor steels cast or rolled in sections 4 in. or more. Because the cooling rates in these heavy sections are low, even when the part is water quenched, the chance for bainite to form during the quench becomes greater than in smaller sections despite an increase in alloy content to compensate for the heavier sections. Pearlite formation, on the other hand, becomes less likely because generally the pearlite and ferrite transformation is repressed more by the increased alloy content than is the bainite transformation.

Although martensite is the desired quenched structure in armor plate, the bainite transformation products found in the higher alloy steels approach closely enough to martensite in structure and hardness to suggest that their properties after tempering may be, at least to a certain degree, comparable with those of tempered martensite.

Past experience in this research program and the experience of others have resulted in the unfavorable report on the properties of tempered bainite structures in 0.3 per cent carbon steels. If it is recognized that bainite structures reduce the low-temperature notched bar toughness of 0.3 per cent carbon alloy steels tempered to low hardness and that they, therefore, can be presumed to affect disadvantageously the ballistic properties, it then becomes important to establish the degree of toughness depreciation associated with various percentages of bainite and with bainite formed at several temperatures. This information would lead to some idea of the percentages and types of bainite products that can be tolerated in heavy armor plate and hence aid in establishing the necessary alloy limitations. Comparison along this line was made on four heavy armor-plate compositions, using heat treatments that simulate those in commercial operations as well as a number of isothermal treatments intended to produce various mixed bainite and martensite structures. Both room-temperature tensile properties and V-notch Charpy values, the latter also at sub-zero temperatures, were determined on specimens tempered to a hardness of 240 to 260 Brinell after the specific hardening treatment.

It was shown that steels having compositions intended for use in heavy-sectioned armor plate have mostly bainite in the quenched structure when cooled at a rate equivalent to that in a 3-in. water-quenched plate, but the notched bar toughness of the

tempered product remains high even when the cooling rate approaches that of the water-quenched 9-in. plate. Small percentages of pearlite in the microstructure were shown to be highly detrimental. The presence of small percentages of ferrite, on the other hand, did not appear to be too objectionable, provided the balance of the structure did not contain pearlite. Bainite structures produced by isothermal transformation had lower V-notch Charpy values than did structures of martensite tempered to the same hardness. The notched bar values of bainitic structures are improved, however, in going from high-temperature bainite to low-temperature bainite.[131]

As mentioned earlier, the attributes of boron to increase the hardenability of steel and to achieve this increase in hardenability without a concurrent increase in quench-crack susceptibility led to a study of boron in steels suitable for heavy armor with the possibility of obtaining structure appreciably more martensitic in character. As stated earlier, boron added to the hardenability of the steels without conferring other less desirable characteristics.[105]

The sum total of all the investigations on heavy armor indicates that there is no acceptable short-cut to the evaluation of structure and properties at the center of very heavy sections and that actual quenching of heavy sections, cutting them up, and determining the interior structure and mechanical properties will, in the long run, be the best way of obtaining reliable information.

2.4 NONMAGNETIC ARMOR PLATE FOR AIRCRAFT

Prior to World War II, it had been considered that aircraft armor should be nonmagnetic or magnetically stable so that it would not interfere with the functioning of the magnetic compass. Although the compensating magnets in the compass could correct for the effect of steel in the engine and in structural parts, aircraft armor appeared to change its polarity continually so that compensation could not be satisfactorily accomplished.

In the Spring of 1941, the Bureau of Ordnance, Navy Department, urged NDRC to investigate steels of the nonmagnetic type, pointing out that if nonmagnetic armor of standard type could not be developed, it would be helpful if the magnetic stability of aircraft armor could be increased. This problem was also of interest to the Army Air Forces under control number AC-6.

Accordingly, the Metallurgy Section of the former Division B, NDRC, established Projects B-104 and B-208 (AC-6) (NO-B13), Development of Non-Magnetic Armor Steel, at the Massachusetts Institute of Technology in July 1941. The program included a survey of the requirements as well as the materials available for nonmagnetic armor and a laboratory investigation of these materials. This investigation included studies of steel making methods, heat treatment, metallographic studies, and tests, such as magnetic tests, hardness tests, tensile tests, and ballistic tests.

The principal phase of the investigation was a study of Hadfield's manganese steel as it was the most promising of the nonmagnetic materials available. It contains usually 1.0 to 1.4 per cent of carbon and 11 to 14 per cent of manganese and, when quenched from above 1800 F, it is nonmagnetic. Its properties were varied by changes in composition through the use of alloy addition agents, cold work, and heat treatment. Forty-three heats of steel of this general type were made, forged, and tested.[132, 133]

The hardness, yield strength, and ultimate tensile strength in the quenched state are increased by additions of silicon, chromium, molybdenum, tungsten, and vanadium. At the same time, ductility is sometimes diminished but never below an elongation of 20 per cent in 2 in. Aluminum and nickel have a slight softening effect but at the same time increase the elongation and tensile strength.

Cold reduction increases the hardness and tensile strength of all specimens tested. Many but not all of the steels retained most of their ductility even when cold rolled to a hardness of 35 Rockwell C. In most cases the steels retained their nonmagnetic character.

Heat treatment in the form of tempering or aging at 500 to 1100 F caused a slight increase in hardness and generally a marked decrease in ductility. At the same time, many of the steels became magnetic. In no case could it be said that the properties were improved by heat treatment.

Several compositions had good physical properties and were nonmagnetic in the quenched or cold-rolled states, although they were somewhat magnetic after rupture in tension. These and several related compositions offered considerable promise as nonmagnetic armor and investigations of their bal-

listic properties were made at Watertown Arsenal and the Naval Proving Ground.[134]

In none of these ballistic tests on specimens of armor $\frac{3}{8}$ in. thick was the ballistic limit as high as that of good homogeneous armor plate. It was found that penetration resistance was improved by cold rolling, giving rise to a slight increase in magnetic permeability in most cases. Tempering at any temperature failed to improve and often lowered the ballistic properties.

2.5 INDEXING OF DIVISION 18 REPORTS ON ARMOR

An index of the Division 18 reports on armor was prepared by the Research Information Division of the War Metallurgy Committee. This index[135] gives a subject list of the various projects with the reports issued on each, a brief abstract of each report, and a subject index of the reports. It is believed that this index will enhance the usefulness of the many reports on the subject.

Chapter 3

GUNS AND GUN STEELS

3.1 INTRODUCTION

The Division 18 program on guns and gun steels embodied nine research investigations. These included studies of the steel quality required for wrought gun tubes, improvement in gun steel ingot practice, the prevention of cracking in gun tubes, the heat treatment of gun steels, the control of steel making and plant practice in the manufacture of seamless gun tubes, and the development of new gun steels of improved physical properties.

The various projects were established as the result of suggestions of the Research Group of the Subcommittee on Gun Forgings, Ferrous Metallurgical Advisory Board, Army Ordnance Department; Watertown Arsenal; and Watervliet Arsenal. These organizations cooperated very closely with the War Metallurgy Committee in the conduct of the projects. The work resulted in an increased output of large guns of all sizes and much better testing procedures, insuring higher quality in the finished guns. In one instance, simplified testing procedures based on the NDRC studies reduced the number of required tests by 75 per cent, thus making substantial savings in time, manpower, and testing equipment. It has been estimated that the annual savings as a result of this one development might have amounted to $1,000,000, a sum more than twice the total cost of the entire Division 18 gun steel research program.

The results of these studies were distributed in NDRC reports to the Armed Services and to all the manufacturers of gun forgings supplying gun tubes to Army Ordnance. The latter comprised the membership of the Subcommittee on Gun Forgings, Ferrous Metallurgical Advisory Board, Army Ordnance Department.

3.2 STEEL FOR GUN TUBES

The quality of gun steel is considered good if the gun tube behaves satisfactorily when used in the manner for which it was designed, and if when worn out it endured a normal useful life.

In the spring of 1941 the following major questions arose with respect to gun steel quality:

1. What minimum steel quality is essential for the best performance of gun tubes?
2. What tests are of the most value for measuring this quality?
3. Does practically all gun steel produced have a quality higher than that essential for best performance?
4. Do specifications for gun tubes insure that (a) all tubes accepted have adequate quality, and (b) all tubes rejected have inadequate quality for good performance?

Answers to these questions were considered important because it was believed that from them could be determined the kind of research program likely to be most valuable to the Armed Services. For example, if for forgings the minimum steel quality that should be tolerated were known in terms of certain properties such as yield strength, transverse reduction of area, and transverse impact resistance, then a specification could be written utilizing this information. Further, if the quality produced were practically always higher than the minimum required to give best performance, inspection and testing could be reduced to a minimum. Under these conditions, research to improve the steel quality of gun tubes would tend to be discouraged.

When the NDRC program first was started, it was believed that (1) the minimum steel quality essential for the best performance of gun tubes was not known, (2) the best tests for measuring gun steel quality were tensile, impact, macroetch, and proof tests, (3) more than 90 per cent of all steel produced for gun tubes had a quality above the minimum specified and above the minimum required for good performance, and (4) specifications in use in 1941 accepted with considerable certainty only tubes of adequate steel quality.

Most of the gun tube work on NDRC projects was planned to secure information to answer the questions listed above more quantitatively than had previously been possible and to be used in the development of better specifications for the accept-

ance of gun tubes. Practically all work on steel for gun tubes was done on wrought tubes.

3.2.1 Steel Quality of Wrought Gun Tubes

The steel quality of a heat-treated gun tube forging is said to be good when (1) the yield strength falls between the specification limits, (2) the transverse impact resistance is high, (3) the transverse ductility is high, (4) the forging is free from porosity or unsoundness, excessive nonmetallic matter, and internal and external defects of harmful character.

Yield strength is probably the most important property in gun tubes, and fortunately it is the one about which there is practically complete agreement as to its importance. The magnitude of the pressure a tube of given yield strength and of given dimensions will resist in service before the bore is expanded significantly is quite definitely known. Such knowledge is used in the design of gun tubes and in the establishment of specification limits for yield strength. Minimum yield strength requirements as written into specifications permit liberal allowances for normal variations of yield strength in a tube, among tempering batches, and among heat treatment practices. The choice of a maximum yield strength limit is much more arbitrary than is the choice of the minimum. Some even believe that a maximum yield strength should not be specified at all. Sometimes a maximum hardness but no maximum yield strength limit is specified.

It is often stated that gun tube steel should have maximum toughness at the yield strength level to which the tube is tempered. Maximum toughness is obtained by quenching to martensite and subsequent tempering. Therefore, this statement is likely to be more correct when referring to tubes which will be critically stressed in service and subjected to high circumferential elastic strain, such as in a radial bore strain of 0.003 in. or more,[136] than when referring to ordinary gun tubes. It may be that practically all the ordinary gun tubes of large wall ratios, 2.0 or above, and worn out by erosion, perform just as well whether they have or have not maximum toughness providing that the yield strength is adequate. Despite this, it is probably well worth while to try always to develop the maximum toughness at a given yield strength, since tubes with maximum toughness when subjected to stresses developed by premature explosions are less likely to fragment into as many small pieces as tubes with inferior toughness. Frequently, however, because of size effect it is not possible to develop maximum toughness by quenching completely to martensite and drawing to the required yield strength.

The uncertainty concerning the toughness is required in the average gun tube, for best performance has led to much controversial discussion regarding the choice of minimum transverse reduction of area and minimum transverse impact values to be written into specifications. Opinions have varied from the one extreme that no minimum transverse reduction of area and no minimum transverse impact resistance values should be specified for the acceptance of the garden variety of gun tubes, to the other extreme that minimum transverse reduction of area and minimum transverse impact requirements should be as high as possible, providing they do not cause a serious loss in production. As a result of the work done at Watertown Arsenal and by NDRC, more is known now about the relation between transverse impact resistance and performance and the relation between transverse reduction of area and performance than was known at the beginning of World War II.

Watertown Arsenal has reported that many tubes of recent design which are critically stressed in service develop progressive damage to the extent that they must be taken out of service before they are worn out by erosion. If this were not done it is believed such tubes would finally burst. Obviously it is much more serious to have tubes fail because of progressive stress damage than because of erosion. More recent results from Watertown Arsenal have indicated that the higher the impact resistance at a given yield strength, the better the tube will resist progressive stress damage. It was decided on the basis of Watertown Arsenal's findings on progressive stress damage that every effort should be made to determine what factors cause progressive stress damage and how this damage can be avoided. Work on this problem was started under NDRC and continued under an Army Ordnance contract supervised by Watertown Arsenal. Watertown Arsenal recommended that specifications used for the acceptance of those gun tubes likely to suffer seriously from progressive stress damage should include an impact requirement, and this recommendation was accepted by Army Ordnance. Statistical studies were made under Project NRC-38 (OD-34-3), Im-

provement in Wrought Gun Tubes, conducted by Carnegie Institute of Technology. These studies yielded the highest transverse impact values at various yield strength levels which could be specified without causing any serious loss of production. These values were accepted tentatively by Army Ordnance and were written into U. S. Army Specification 57-106A after minor changes had been made by Watertown Arsenal.

Since the establishment by the Metallurgy Section of the former Division B, NDRC, of the initial investigation, Project B-90 and B-160 (OD-34-3), Steel for Gun Tubes, it has been the opinion of the investigators at Carnegie Institute of Technology that, down to well below an *average* transverse reduction of area of 20 per cent, the effect of transverse ductility in gun tubes on their performance is practically insignificant, providing the tubes in service fail by erosion.[137] In one investigation an attempt was made to determine whether or not the performance of four 37-mm M6 tubes with transverse reduction of area which averaged between 19 and 26 per cent was inferior to the performance of two similar tubes with averages of 43.8 and 39.6 per cent, respectively. The 19 to 26 per cent averages represent material of the lowest reduction of area in the transverse direction [RAT] values likely to be accepted under specification 57-105-1, whereas the 43.8 and 39.6 per cent averages represent material of high RAT quality. In this study a frequency curve was determined for each tube which indicated roughly the magnitude of the variation of RAT per tube and the average RAT for each tube. No significant difference could be found between the performance of the two 37-mm M6 gun tubes with high transverse ductility (average RAT, 40 per cent) and the performance of the four 37-mm M6 tubes with low transverse ductility (average RAT, 20 per cent). The tube with the lowest RAT quality (average RAT, 19.8 per cent) had the longest life. The results suggested that some variable or variables other than RAT had a much more significant influence on gun life and that the relation between RAT and performance was relatively of minor importance. All six tubes failed because of excessive erosion and scoring and not because of progressive stress damage. It was tentatively concluded that transverse ductility down to 20 per cent average RAT does not control the length of useful life or the performance of tubes which fail by erosion. It was pointed out, however, that it is not known whether transverse reduction of area is an important variable in those gun tubes whose useful life is controlled by progressive stress damage rather than by erosion.[a] The 75-mm M6 and 76-mm M1A2 tubes are in this class.[138] Probably RAT does tend to influence the behavior of tubes with respect to progressive stress damage, since a deficiency of impact resistance aids the development of such damage and a positive correlation has been found to exist between impact resistance and transverse reduction of area among tubes from different heats. Of the several hundred tubes used in the determination of the correlation, those from low average RAT heats usually gave low transverse impact averages and those from high average RAT heats usually gave high transverse impact averages. All tubes were severely quenched before being tempered and there was no reason to suspect that temper brittleness or an inadequate quench was responsible for the low impact values observed. The yield strength level selected for the study was 150,000 psi.

3.2.2 Significance of Tests Used in Determination of Gun Tube Quality

Most tubes which are worn out fail because of erosion. Some are taken out of service because the probability of the development of serious progressive damage in tubes continued in service for a longer period is considered too high. Practically none fail because of a deficiency of yield strength or because of extraneous metallurgical defects, such as cracks, voids, or bore defects. Apparently, the tensile test used to insure adequate yield strength and the macroetch and visual tests used to insure freedom from damaging defects in accepted tubes have been extremely effective in achieving the objectives sought.

It is believed that gun tube steel quality bears no significant relation to erosion. Much more important factors which control erosion are the character of the projectile and the conditions of use.

Since tubes of maximum toughness at a given

[a] Due consideration must be given to the limitations imposed by this small number of firing tests. Rigid general conclusions from these tests alone are not possible in view of the effect of type of failure and the relation thereto of specific designs and character of service. Specifications cannot be influenced until more data are available.

yield strength resist progressive stress damage better than do others, a Charpy impact requirement is included in U. S. Army Specification 57-106A to insure that all tubes subjected to conditions which normally cause serious progressive stress damage shall have more toughness than the specified minimum.

Under Project NRC-38 (OD-34-3) carried out at Carnegie Institute of Technology, a study was made of the significance of the various tests used in determining the quality of gun tubes. Statistical studies were made also to determine the minimum requirements for yield strength, transverse impact, and transverse reduction of area.

Transverse Tensile Test for Wrought Gun Tubes

In this test yield strength, tensile strength, transverse elongation, and transverse reduction of area values are determined. Of these, the yield strength value is important for reasons already mentioned, but the tensile strength value is relatively unimportant. To what extent transverse elongation and transverse reduction values are of value is open to considerable question, primarily because too little is known about the relations between transverse elongation and gun tube performance, or between transverse reduction of area and gun tube performance.

It is quite certain that a minimum yield strength requirement should always be specified for the acceptance of gun tubes. It is not at all certain, however, that a minimum transverse elongation or a minimum transverse reduction of area should be specified. Nevertheless, with present knowledge such minima in specifications are the best known assurance of adequate quality. Probably much more transverse ductility is needed in tubes to be autofrettaged than in others.

Transverse Charpy Impact Test for Wrought Gun Tubes

It already has been pointed out that by use of this test in U. S. Army Specification 57-106A assurance is given that tubes which usually suffer severely from progressive stress damage practically always have a certain minimum toughness. For this reason the impact test is considered important. The present level of this minimum is sufficiently low to allow acceptance of almost all tubes of the types referred to above. The extent to which the impact test requirements causes an increase of average toughness or an increase of minimum toughness in accepted gun tubes is not known, so that a quantitative evaluation of the usefulness of the test cannot be given, although it is probable that significant benefits have been obtained directly or indirectly by specifying an impact test. The direct beneficial effect results from the rejection of a few tubes of very low impact resistance, and the indirect beneficial effect, which is probably much more important, results from the extra efforts made by producers to insure that the average impact resistance quality shall be so high that no tubes are likely to fail because of deficiency in impact resistance when presented for inspection. Improved impact quality may result from the use of a steel of higher alloy content, a more severe quench before the temper, and an improved tempering procedure to avoid temper brittleness.

The significance of this test has been thoroughly discussed in Watertown Arsenal reports and in publications by the Arsenal's personnel.

Macroetch Test

The macroetch test has been used with considerable success for locating extraneous defects in gun tubes, such as all kinds of cracks, flakes, porosity or unsoundness, excessive nonmetallic matter, and bore defects.

Often when disks are etched, especially when they come from large tubes, the acid attacks some regions faster than others with the result that the etched surfaces to be examined show numerous deep holes which are usually round. Such holes in macroetched disks from 8-in. howitzer forgings have been observed to be as large as $\frac{1}{4}$ in. deep and $\frac{1}{8}$ in. in diameter. It is imperative that these holes and the apparent porosity caused by the etchant not be confused with the voids and true porosity which obviously may be present in a tube before etching. At the beginning of World War II, the quality of macroetched disks having this appearance was considered inferior by many inspectors and for a time they rejected tubes from which such disks were cut.

Several tensile specimens were cut from disks such as those referred to above, and RAT values were determined. The results showed very definitely that transverse reduction of area is on the average quite as high for specimens taken from those regions most rapidly dissolved by acid as for specimens taken from regions least rapidly dissolved by acid. Additional studies indicated that the average

RAT value for specimens from a macroetched disk containing a considerable number of etched-out holes is about as high as the average RAT value for specimens from a comparable macroetched disk relatively free from the etched-out holes. When inspectors became aware of these results, tubes were not rejected simply because macroetched disks from them showed round holes or pits such as those described above.

Other work indicated that the quality of forgings with respect to transverse ductility cannot be judged from the dendritic pattern observed among macroetched disks, at least for the range of pattern variation studied at Carnegie Institute of Technology under Project NRC-38. It was shown that the macroetch test has but a limited usefulness in showing the depths to which forging has penetrated and destroyed the pattern.[139]

Proof-Firing Test

The proof-firing test is essentially a performance test in which at least one round is fired at about 115 per cent of normal pressure. The bore of any tube deficient in yield strength will expand when proof fired. One advantage of the proof-firing test over the others referred to earlier is that the entire tube is involved.

There is considerable assurance that tubes of types which normally do not suffer seriously from progressive stress damage and which meet proof-firing test requirements will behave satisfactorily in the field and will not fail because of inferior steel quality. However, the proof-firing test does not insure that a tube subjected to conditions responsible for serious progressive stress damage will not fail within its normally expected useful life. One tube with low impact resistance which met proof requirements failed because of progressive stress damage after about three rounds, while a similar tube which also met proof requirements failed by progressive stress damage after 1,800 rounds. This tube also had a low impact resistance. Since the proof-firing test does not necessarily insure that those tubes of certain designs, that is, the 75-mm M5, which meet the test requirements will not fail by progressive stress damage within their normally expected lives, it is imperative that such tubes have considerable toughness or high impact resistance. Tubes with high toughness resist progressive stress damage better than do tubes of low toughness.

3.2.3 Primary Objective Sought as a Result of Statistical Studies

One of the major objectives of the work done under Project B-90 and B-160, Steel for Gun Tubes, and Project NRC-38, Improvement in Wrought Gun Tubes, was to supply information based on a statistical analysis of transverse tensile and transverse impact test data so that a specification could be written which would give an extremely high degree of assurance that the steel quality of accepted wrought gun tubes[b] with respect to yield strength, transverse impact, and transverse reduction of area would be above the minimum needed for good performance, and that only an extremely small number of tubes having more than the minimum required would be rejected. In addition, it was desired that new specifications for gun tubes should require less inspection and testing than formerly.

To attain the objectives sought every effort was made to determine (1) the quality needed, (2) the quality produced, and (3) the minimum requirements for yield strength, transverse impact, and transverse reduction of area which should be specified in order to guarantee with better than a 99 per cent certainty that no tubes with less than the minimum needed for good performance would be accepted. As a result of these efforts, specifications for gun tubes written by Army Ordnance and in use at the end of World War II were far superior to those in use at its beginning.

3.2.4 Minimum Quality Needed and Specification Requirements

The fundamental weakness of most specifications, including those for gun tubes, is that generally they are based on what quality is produced or can be produced, rather than on what quality is needed. Unfortunately, information relating to the required quality is generally so scanty as to make it impossible to write a specification which will accept all material of a quality above the minimum needed and will reject all other material.

From results obtained under NDRC Project NRC-38 (OD-34-3) and from results supplied by Water-

[b] Wrought gun tubes consist of (1) seamless tubes, and (2) forgings. Work on centrifugal castings similar to that referred to above is now being done at Carnegie Institute of Technology under a direct contract with the Army Ordnance Department.

town Arsenal the following conclusions can be drawn.

1. The minimum required yield strength needed is relatively well known. The minimum given in specifications was determined from available information about (a) the minimum needed and (b) the variation of yield strength normally present in tubes submitted for inspection.

2. The highest possible value of transverse impact resistance is necessary, at least for tubes likely to suffer seriously from progressive stress damage. The minimum needed for other tubes which normally fail by erosion is not well known; it is frequently accepted as being so low that no minimum need be specified. The minimum transverse impact requirement specified in U. S. Army Specification 57-106A for acceptance of tubes likely to suffer seriously from progressive stress damage was determined more by production impact resistance quality than by what impact resistance was thought to be needed for the best performance of gun tubes. If the production quality had been higher than it was in World War II, then the minimum transverse impact requirement specified in 57-106A would probably have been higher also.

3. The minimum transverse reduction of area needed is not known. It appears probable from work done[140] that the RAT quality produced is practically always above the minimum needed for the good performance of gun tubes and above the minimum specified.

On the basis of information presented in the above summary, it is believed that specifications for yield strength as set by Army Ordnance in U. S. Army Specification 57-106A and in appropriate drawings are about as they should be. Specification requirements for RAT, which are now so low that they are unlikely to cause more than an insignificant number of rejections, should remain unchanged, at least until RAT needs are much better known and more clearly defined than at present. Specified minimum transverse impact requirements for tubes likely to suffer severely from progressive stress damage should be raised whenever that can be done without interfering seriously with production.

3.2.5 Relation Between NDRC Investigations and Development of Army Ordnance Specifications

After the minimum specifications were determined with respect to yield strength, transverse reduction of area, and transverse impact, the next problem was to write specifications insuring that only tubes of adequate yield strength, transverse reduction of area, and transverse impact resistance be accepted. It was necessary to make a thorough statistical analysis of gun tube tensile and impact data in order to obtain the information required for the best solution of the problem. This analysis was started under NDRC Project NRC-38, Improvements in Wrought Gun Tubes, at Carnegie Institute of Technology and is continuing under a direct contract with Army Ordnance. Obviously, a complete statistical analysis of all existing tensile and impact World War II data is very time consuming, involving the use of approximately one million data. Fortunately, extremely valuable results were obtained on the basis of a study of about one-fifth of the total data available.

Before Army Ordnance could write a new specification which would allow production of gun tubes to operate as efficiently as possible and at the same time would guarantee that only tubes having more yield strength, transverse reduction of area, and transverse impact than the minimum would be accepted, it was necessary to know what quality of product with respect to the properties indicated was being submitted for inspection.

Under Project B-90 and B-160, Steel for Gun Tubes, and Project NRC-38, Improvement in Wrought Gun Tubes, investigations were carried out at Carnegie Institute of Technology to determine the following:

1. Average transverse reduction of area quality.
2. Transverse reduction of area variation.
3. Degree of control of transverse reduction of area.
4. Average yield strength quality.
5. Yield strength variation.
6. Degree of control of yield strength.
7. Average transverse impact quality.
8. Transverse impact variation.
9. Degree of control of transverse impact.
10. Relation between yield strength and transverse reduction of area.
11. Effect of reheat treatment (requench and draw) and redraw on transverse reduction of area.
12. Relation between yield strength and transverse impact.
13. Effect of forging reduction on transverse reduction of area.

14. Effect of angle of test, relative to fiber direction, on transverse reduction of area and on transverse impact resistance.

Average Transverse Reduction of Area Quality

Statistical studies to determine average RAT quality of tubes presented for inspection were made first using RAT data for seamless tubes. There were several reasons for this procedure. Seamless tubes were not used in any war before World War II. Furthermore, the specification written for the acceptance of such tubes was considered imperfect and was for temporary use only until a better specification could be developed. Seamless tubes were made from high RAT heats and were quenched and heat treated using practices which, with modern metallurgical knowledge, should give an excellent uniformity of product. Furthermore, early in World War II, seamless tubes were being produced at a rate of about 6,000 per month (4,000 40-mm M1 and 2,000 75-mm M3). Since heat lots consisted of a very large number of tubes, usually more than 250 40's and 100 75's per heat, the probability that the war effort would benefit quickly and significantly from results of statistical studies seemed high.

The average RAT quality of seamless tubes was found to be about 50 per cent for 40-mm tubes, 41 per cent for 75-mm M3 tubes, and 48 per cent for a few 75-mm howitzers. Average yield strengths were approximately 110,000 psi for 40-mm M1 tubes, 115,000 psi for 75-mm M3 tubes and 110,000 psi for the 75-mm howitzers. The lowest and highest heat RAT averages[c] were found to be 42.5 per cent and 56.0 per cent for 40's, 34.8 per cent and 48.0 per cent for the 75's and 47.7 per cent and 48.4 per cent for the howitzers. Heat RAT averages were determined for about 150 40-mm heats, 250 75-mm M3 heats and 3 75-mm howitzers heats. The averages determined for tubes were found to be usually about the same as their respective heat averages. The maximum difference, based on a large number of values, between a tube RAT average and the heat RAT average generally was found to be less than 3 per cent, although there was some indication that the maximum difference between a tube and heat average might be occasionally 5 per cent or 6 per cent higher. By requiring that the minimum average quality of 40-mm M1 and 75-mm M3 tubes accepted as heat lots shall be at least 6 per cent higher than the minimum average quality of tubes accepted as individual tubes (by the prescribed method of sampling and testing), it is more than 99.9 per cent certain that the minimum average RAT quality of any tube accepted in a heat lot is not less than the minimum average RAT quality of any tube accepted on an individual rather than on a heat lot basis. This conclusion was reached because all statistical evidence supported the belief that this higher minimum average quality required of tubes accepted in heat lots is sufficient to insure that differences between tube RAT average and the heat RAT average, and differences between the maximum variation of RAT in a tube and the maximum variation of RAT among all the tubes of the heat, are small enough so that the minimum RAT quality of accepted tubes is not lowered.[141]

Statistical studies of RAT values for forgings were much less complete than were those for seamless tubes. Data for forgings from all companies of all sizes, 37 mm to 16 in., give heat RAT averages which fall between limits of about 30 per cent and 55 per cent at a yield strength level of about 110,000 psi, between 30 and 50 per cent at a level of 130,000 psi, between 25 and 40 per cent at a level of 150,000 psi, and between 20 and 38 per cent at a level of 165,000 psi.

Transverse Reduction of Area Variation

The observation that RAT at a given yield strength varies considerably in all gun tubes and the realization of the importance of this fact in its relation to specifications was probably the most important single result of the statistical work done on gun tubes under NDRC. It changed completely the fundamental approach to the problem of writing gun tube specifications. Specifications were subsequently written by the Army Ordnance Department substituting a statistical approach for the one previously used, and the benefits derived by both the Army Ordnance Department and producers of gun tubes were considerable.

Statistical studies of RAT values for specimens from seamless tubes of 40-mm M1 and 75-mm M3 sizes indicated that the maximum variation of RAT usually is about the same in a small section of a gun tube as (1) in the whole gun tube, (2) among all the gun tubes from one ingot, and (3) among all

[c] All RAT values for heat-treated seamless tubes from a given heat are averaged and this is called the heat RAT average. Actually the *true* heat averages for 40-mm heats may be slightly lower than given, because specimens for tensile tests of 40-mm tubes were cut from the upset breech ends. Values for upset ends are on the average about 3 per cent higher than for other parts of the tubes.

the gun tubes from a heat. In poor quality heats the maximum RAT variation among the tubes is usually higher than among tubes from good heats. The maximum variation observed was rarely less than 20 per cent from a minimum of 35 per cent RAT to a minimum of 55 per cent RAT at a yield strength of 120,000 psi. It was obvious from these results that to establish RAT quality precisely a large number of RAT values are required. A single value has practically no meaning except as it relates to other values. Fortunately, since tubes from a given heat are usually about alike, and since a large number of tubes, usually from 100 to 300 or more, are generally made from the same heat, a tensile test per tube is not necessary for the determination of the RAT quality of the heat, and within the desired accuracy, the RAT quality of any tube in the heat. Obviously, for the determination of RAT quality in a large unit, the larger the number of small units (tubes) making up the large unit (heat or practice), the smaller the number of RAT values per small unit required. Generally more than 100 seamless 75-mm M3 and 200 seamless 40-mm M1 tubes were made per heat and many fewer tests than one per tube were necessary to evaluate the RAT quality of a heat.

From the above discussion and from other facts previously stated in this summary, it is much more desirable to consider the heat unit, or even a large unit, rather than the individual tube unit as the logical unit to use in specifications of RAT quality for wrought gun tubes. This is especially true when the product presented is consistently excessively good or excessively bad. The use of the heat lot unit in Specification WVXS-78, developed by the Army Ordnance Department on a basis of this NDRC investigation, resulted in the saving of about 100,000 tensile tests in one year during World War II. Other savings of tests, not yet estimated but known to be quite considerable, have resulted from the use of the heat unit concept in other specifications developed later in these studies, namely, WVXS-88, WVXS-95, and U. S. Army Specification 57-106A used for the acceptance of gun tube forgings. Of course, when the heat is of borderline RAT quality, the use of the individual tube unit in specifications may be justified since, as already pointed out, the average RAT value of the worst tube in a heat may occasionally be 6 per cent or more lower than the average RAT value of the best tube in the same heat.

In general, studies of RAT data for gun tube forgings of sizes from 37 mm to 16 in. confirmed the above conclusions.

Degree of Control of Transverse Reduction of Area

When RAT determinations are made on specimens from breech and muzzle ends and a tube is accepted or rejected on a basis of these RAT values, it is at least tacitly assumed that the RAT quality of the whole tube is indicated by the RAT quality of muzzle and breech ends. When a whole heat of tubes is accepted or rejected on a basis of RAT values for specimens from the breech (or muzzle) ends of some, but not all, of the tubes, then the assumption has been made that the RAT quality of the whole heat is indicated by the RAT quality of the breeches (or muzzles) of the tubes tested. The extent to which these assumptions are justified is determined by the degree of RAT control resulting from a given practice. Fortunately, so far as is known, these assumptions have never been sufficiently in error to have allowed, either at the proving grounds or in the field, the failure of accepted gun tubes owing to RAT deficiency.

Statistical studies were made to determine as quantitatively as possible the degree of control of RAT achieved in the various practices used by producers of gun tubes in World War II. Plotted control charts[140,141] reveal that the degree of control of RAT in tubes, among tubes in a heat, and among heats in a practice is usually sufficient to justify the use of the known laws of chance for the determination of RAT quality in gun tubes. By use of these laws of probability to determine RAT quality, advantages of considerable practical importance were gained by both the Army Ordnance Department and the gun tube producers. Thousands of RAT data were used for the plotting of the control charts, but despite the overwhelming evidence of the validity of the conclusions drawn, the consequences of its acceptance are still viewed with scepticism by many inspectors. Often tubes have been accepted from unusually low average RAT heats because the one (for small tubes), two (for intermediate-sized tubes), or four (for large tubes) RAT values were by chance above the minimum specified. The weakness of such a procedure can be amply demonstrated by examining the results obtained from the statistical analyses. Before long it is probable that specifications will be based

on statistical knowledge with respect to the more efficient selection of good and rejection of poor quality, and with respect to the reduction of the number of tests per tube required for the determination of RAT quality within a required accuracy.

Average Yield Strength Quality

Yield strength values, maximum and minimum, are usually chosen by designers of gun tubes. They vary, of course, with the size and type of tube and with the purpose for which the tube is to be used. Therefore, the average yield strength quality must be considered in relation to the values chosen by the designers. For example, if the maximum and minimum yield strength values specified should be 115,000 psi and 95,000 psi, respectively, and the product inspected should have an average yield strength quality of 105,000 psi, then the average yield strength quality would be considered good. The probability of accepting tubes with untested regions above or below the specified limits would be at a minimum.

Statistical studies of yield strength data for practically all sizes and types of gun tubes revealed that initially some producers of gun tubes had difficulty in meeting yield strength requirements after the first quench and temper.[d] This was because the maximum range of yield strength in certain practices was too large to permit observed individual yield strength values to fall always between prescribed limits, and because the average value of the yield strength was too close to the minimum yield strength specified for all the observed individual values to fall above that minimum. Obviously, the producer could easily have tempered his quenched tubes at a temperature a little lower than the one used, to raise his practice average. However, he did not do this in the early months of World War II because he was faced with another problem whose solution also depended on heat treatment; the specification of RAT quality, which is higher for low- than for high-yield strength tubes. RAT values for the acceptance of gun tubes had to be above a certain minimum which was the same over the whole range of yield strength between the maximum and minimum limits specified. Studies were carried out to determine the relation between RAT and yield strength,[142] and subsequently the specification for wrought gun tubes was modified to take this relation into account. As a result, producers in general raised their practice average, and this brought about a drastic reduction in the frequency of occurrence of yield strength values below the minimum specified, and greater assurance that no tube accepted by Army Ordnance would be deficient in yield strength.

[d] A tube with too high a yield strength was retempered while a tube with too low a yield strength was requenched and tempered.

Yield Strength Variation

As far as is now known, the variation of yield strength in gun tubes, which normally fail by erosion, has no significant effect on their performance, provided of course that the tube is not actually deficient in yield strength. However, a tube with a yield strength above the minimum specified and with a very large variation may be so hard in some parts of the tube as to cause trouble in machining. The more uniform the product, the easier it is to standardize machining operations.

As already pointed out, toughness should be as high as possible in those tubes which, if worn out in service, would fail by progressive stress damage. Since impact resistance or toughness is decreased usually at a rate of 2 ft-lb or more for each increase of 5,000 psi in yield strength, it is important that the maximum yield strength be as low as possible. Ideally perfect tubes would have the minimum yield strength necessary for best performance and would be perfectly uniform. In actual practice, the need for a small variation of yield strength for tubes most likely to suffer from serious progressive stress damage must be balanced against what is being or can be produced in industry with sufficient speed and in sufficient quantity to meet production schedules.

The variation of yield strength in 40-mm M1 and 75-mm M3 seamless tubes and forgings is rarely less than 2,000 psi, is usually about 4,000 psi, and may be occasionally as high as 10,000 psi. A producer of seamless tubes and a producer of forgings, both using electrically controlled heating for tempering, produced a more uniform product than did any other producers of gun tubes whose products were studied. The seamless tubes were tempered in a continuous furnace, and one tube followed another of the same heat until all the tubes from that heat had been started through the furnace. Tubes of another heat were then similarly tempered. The forgings mentioned above were suspended in the tempering furnace in such a way as to afford as uniform heat-

ing of all the tubes in the batch as possible. Studies of the variation of yield strength in heavy tubes from good practices are not complete. However, they do show that the maximum variation is on the average more pronounced in large than in small tubes.

In poor practices the variation of yield strength in gun tubes was found to be rarely below 2,000 psi, usually about 10,000 psi, and occasionally as high as 30,000 psi. Variations of these magnitudes have been observed in 37-mm tubes.

The maximum variation of yield strength among tubes in a heat lot[e] or in a batch was found to be on the average about 10,000 psi in a good practice. Occasionally a variation as high as 20,000 was observed. In poor practices the maximum variation per batch was on the average about 30,000 psi and occasionally a variation as high as 50,000 psi was observed. It was found that the maximum variation of yield strength in batches containing tubes from several heats was on the average much higher than in batches containing tubes from only one heat. When this information became available, at least one producer immediately changed his practice of using mixed-heat batches to that of using only one heat per batch, with the result that the maximum variation per batch dropped on the average to about one-half of what it had been before.

Degree of Control of Yield Strength

Control-chart studies[143] indicated that for each of about half the practices considered the variation of yield strength in one heat lot was about the same as in another from the same practice, and the variation of yield strength in one batch was the same as in another from the same practice. A few exceptions to this general conclusion were noted. Variations were observed among the heat lot or batch averages in each of the practices. These were usually of relatively small practical importance. As long as the quality of control observed in each of the above practices remains unchanged, the yield strength quality of a tube from any one of the practices may be predicted, both with respect to the average for the tube and its variation, within an accuracy of 5,000 psi. Such a prediction probably would be correct within the amount mentioned more than 99 times out of every 100.

[e] As long as one tube immediately follows another from the same heat through a continuous tempering furnace, all the tubes from that heat considered together comprise a heat unit or heat lot.

Practices of other producers were in much poorer statistical control than those just mentioned. As a result, more information is required per tube or per batch to indicate within a given accuracy what the yield strength quality of a tube or batch from these producers is likely to be.

In considering the overall picture of variation of yield strength among tubes, it was observed that the maximum variation in seamless tubes was 29,000 psi for 40-mm M1 tubes, and 27,000 psi for 75-mm M3 tubes. The maximum variation observed among 3-in. forgings was 18,000 psi. In each of the remaining practices, a maximum variation of more than 50,000 psi was observed, indicating poor control.

Average Transverse Impact Quality

As previously indicated, transverse impact quality should be as high as possible in those tubes which, if worn out in service, would fail by progressive stress damage. For this reason the Army Ordnance Department decided to specify an impact requirement for the acceptance of such tubes and needed to know what values should be written into the specification to insure the best compromise between quality accepted and production losses. A correct choice of such values depends on a knowledge of how critical is the need of transverse impact quality at various levels for good performance, and what quality is being produced by industry. Under Project NRC-38, a study was made of quality of material being produced with respect to average impact, variation of impact, and control of impact.

Average transverse impact quality varies with yield strength.[142] Therefore, transverse impact averages or single values have meaning only as they relate to yield strength. An increase of yield strength of 5,000 psi usually causes a decrease of 2 ft-lb or more in transverse impact resistance.

With few exceptions, the average transverse impact quality of any one tube in a heat lot or batch was essentially the same as that in any other tube from the same heat lot or batch. Differences of considerable magnitude were observed among averages of heat lot and among averages of batches. At a yield strength level of about 165,000 psi, the difference was 8 ft-lb among heat lots of seamless tubes (17 minimum, 25 maximum), 9 ft-lb among batches of forgings from one producer (17 minimum, 26 maximum), and 7 ft-lb among batches of forgings

from another producer (19) minimum, 26 maximum). On rare occasions the differences are larger than indicated. Occasionally some tubes in a batch are, while others are not, quenched drastically enough to give high impact values in the tempered material, and this causes large differences of average transverse impact quality among the tubes.

Differences among practice transverse impact averages were usually small. In the case of two producers, each making 76-mm tubes, the practice averages were 26 ft-lb and 29 ft-lb, respectively. The yield strength level was about 150,000 psi. Among three producers making 75-mm M5 or M6 tubes, the practice averages were 22 ft-lb for each of two of the practices, and 24 ft-lb for the third with a yield strength of about 165,000 psi. Obviously, at a lower yield strength level, the practice average transverse impact quality is higher. One practice average of 45 ft-lb was observed when the yield strength level was about 115,000 psi. This was for 155-mm mortars.

Transverse Impact Variation

Statistical analyses of a large number of data from each of several tubes and a large number of data from various commercial practices indicate that the maximum variation of transverse impact in a gun tube is usually about (1) 10 ft-lb at each yield strength level in the range between 95,000 and 150,000 psi, (2) 8 ft-lb between 150,000 psi and 170,000 psi, and (3) 6 ft-lb between 170,000 psi and 185,000 psi. Occasionally, one part of a tube may be quenched so much more effectively than another part of the same tube as to cause a much larger variation of transverse impact resistance in the tempered tube than would be expected normally. Values as low as 4 ft-lb and as high as 25 ft-lb have been obtained for specimens cut from one tube. Otherwise, the maximum variation of impact in any one tube from a heat lot or batch is practically always about the same as that in any other tube from the same heat lot or batch.

Degree of Control of Transverse Impact

Considerably more work must be done before the degree of control of transverse impact in a practice, and throughout industry as a whole, can be defined completely.

Control charts indicate that each tube in a batch usually has essentially the same impact quality (average and variation) as any other tube from the same batch.

Impact quality differences of considerable magnitude exist among batches in each practice studied. For batches consisting of tubes from only one heat, these differences result primarily from a variation of batch average transverse impact quality, since the difference of variation of transverse impact quality in one batch as compared with that in any other from the same practice is rarely sufficiently large to be of any practical significance. In any one of the better practices, impact averages for batches consisting of tubes from only one heat in a batch varies by about 7 ft-lb at a yield strength level of 165,000 psi. At lower yield strength levels, the differences among batch averages in a practice are higher.

Relation between Yield Strength and Transverse Reduction of Area

Studies were made to determine linear correlations among the various properties disclosed by the tensile test and the impact test in quenched-out and tempered gun tubes. It was found that in the yield strength range of 95,000 psi to 180,000 psi a good linear correlation exists between yield strength and transverse reduction of area and that an increase of 5,000 psi in yield strength causes a decrease of about 1.5 per cent in transverse reduction of area.[142]

This information was used by the Army Ordnance Department in the development of specifications WVXS-88, WVXS-95, WVXS-131, and the U. S. Army Specification 57-106A. In general, use of the above relation in specifications encouraged each producer of gun tubes to raise his practice average for yield strength. This had two beneficial effects: (1) it decreased the possibility of accepting tubes with a deficiency in yield strength, and (2) it drastically reduced the frequency of redraw and of requench and draw treatments. The percentage of redraw and of requench and draw treatments, which at least in one instance was more than 40 per cent of the total treatments made, was reduced to below 1 per cent.

Effect of Reheat Treatment (Requench and Draw) and Redraw on Transverse Reduction of Area

Studies of the effect of a redraw and of a requench and draw on transverse reduction of area led to the conclusion that at a given yield strength

neither a redraw nor a requench and draw improve the average RAT of gun tubes, providing they were quenched out before the first draw.[144] The effect of a redraw and of a requench and draw on transverse reduction of area in very heavy tubes is uncertain. Laboratory results showed that a redraw improved the transverse reduction of area average for one tube but had no effect on the average for another tube, and a requench and draw did not improve the transverse reduction of area average.

On the basis of the above information, specifications were written which encouraged producers not to redraw nor to requench and draw tubes which fail for transverse reduction of area, unless there was evidence that such tubes were improperly heat treated. As a result, redraws and requench and draw treatments, supposedly made in order to improve transverse ductility at a given yield strength, were reduced very greatly.

Relation between Yield Strength and Transverse Impact

As previously pointed out, studies were made to determine linear correlations among the tensile and impact properties in quenched-out and tempered gun tubes. It was found that between 95,000 and 180,000 psi a correlation exists between yield strength and transverse impact such that an increase of 5,000 psi in yield strength usually results in a decrease of 2 ft-lb or more. An excellent correlation between yield strength and impact was observed in each tube used in correlation studies, but the relation was found to vary among tubes. In 40-mm M1 and 75-mm M3 seamless tubes, a 5,000 psi increase of yield strength results in a decrease of 2 ft-lb in transverse impact, while in 75-mm M5 and 76-mm tubes from a producer of forgings, a 5,000 psi increase of yield strength results in a decrease of 3 ft-lb in transverse impact.

The relationship between yield strength and impact was taken into account by the Army Ordnance Department in writing Specification WVXS-95 and U. S. Army Specification 57-106A. As these specifications were written at yield strength levels above 150,000 psi, it is more difficult to meet the minimum impact requirement than at lower yield strength levels. Tubes which usually just meet specification impact requirements at 140,000 psi will practically always fail if requenched and drawn to 180,000 psi.

Effect of Forging Reduction on Transverse Reduction of Area

Studies showed that with increasing forging reduction the average for transverse reduction of area increased at first, passed through a maximum (probably at below 4:1 reduction), decreased rapidly, and finally decreased more slowly. Also, with increasing forging reduction, the average for longitudinal reduction of area at first increased rapidly, reached a maximum value (probably at below 4:1 reduction), and then remained practically constant.[145]

There were those in Army Ordnance who believed that the effect of forging reduction on transverse ductility should be taken into account in specifying minimum transverse reduction of area requirements for the acceptance of those gun tube forgings which, if worn out in service, would be more likely to fail by progressive stress damage than by erosion. For this reason, a higher minimum transverse reduction of area quality was required for the acceptance of forgings (Specification 57-106A).

Effect of Angle of Test (Relative to Fiber Direction) on Transverse Reduction of Area and on Transverse Impact Resistance

As the angle of test is increased from 0 degrees (transverse) to 90 degrees (longitudinal), both average impact and average reduction of area values are increased. However, up to 20 degrees the increase is too small to be of much practical significance.[146] Since the twist of seamless tubes at positions away from the upset or breech end rarely causes the angle between the fiber and the longitudinal axis of the tube to be much above 20 degrees, both average reduction of area and average impact values for nominal transverse specimens cut perpendicular to the longitudinal axis of the tube are not significantly different from comparable true transverse averages for specimens cut perpendicular to the fiber direction. Since the Specification WVXS-131 used for the acceptance of seamless tubes requires specimens to be cut only from muzzle ends of tubes, that is, away from the upset breech end, and in view of the above considerations, modification of Specification WVXS-131 does not appear to be needed.

3.2.6 Specifications

Information accumulated by the investigators on Project NRC-38 resulted in a better understanding of quality needs in gun tubes, especially with respect to transverse reduction of area, and allowed better evaluations to be made of the quality produced with respect to yield strength, transverse impact, and transverse reduction of area than had previously been possible. On a basis of this and other information available to Army Ordnance, specifications for wrought gun tubes were written from time to time during World War II. These specifications are (1) WVXS-78, (2) WVXS-88, (3) WVXS-95, (4) WVXS-131, and (5) U. S. Army 57-106A.

Specification WVXS-78

Specification WVXS-67, adopted February 28, 1942, was found to be inadequate for procurement of cannon tubes made from seamless tubes and heat treated in continuous furnaces, largely because the amount of tensile testing required was excessive. As a result of utilizing statistical methods for considering tensile data for acceptance and rejection of gun tubes, it became possible to develop Specification WVXS-78, effective November 3, 1942. This specification has proved highly efficient in obtaining tubes of a quality equal to or better than those accepted by the older specification and in rejecting tubes of unsatisfactory properties. At the same time, it reduces the number of tests required and encourages the producer to make tubes of higher minimum quality than hitherto in order to take full advantage of the reduced testing features. The specification is applicable to any method of tube manufacture, provided the number of tubes per heat is large and also that the heat treatment is closely controlled.

Under this specification, tubes of superior quality with respect to yield strength and transverse reduction of area are accepted in heat lots, whereas tubes of much poorer quality which are rejected in heat lots often were accepted, at least in part, on an individual tube unit basis.

As a result of replacing WVXS-67 by WVXS-78 for the acceptance of seamless tubes made between November 1942 and February 1944, about 100,000 tensile tests and between 1,500 and 4,000 heat treatments were saved. Because of this, personnel were released for other duties, equipment was released for additional work, the smoothness of operation and of scheduling was improved, and cost was reduced. These savings occurred at a critical period in World War II when a more fruitful utilization of man power and equipment was of utmost importance. The operating characteristics of Specification WVXS-78 are described in detail in Part I of the final report on Project NRC-38.[141]

Specifications WVXS-88

This specification was written primarily for the acceptance of 37-mm gun tube forgings supplied by one company. Tubes having superior transverse ductility are accepted in heat lots, while tubes having poor transverse ductility are rejected in heat lots, but may be accepted, at least in part, on an individual tube unit basis. Tubes are accepted for yield strength in batch lots[f] whenever yield strength data indicate that the batch yield strength average is far enough removed from specification limits and the variation of yield strength in the batch is sufficiently low to insure that all tubes in the batch have adequate yield strengths. However, tubes from failed batches are resubmitted for inspection on an individual tube unit basis.

In WVXS-88, the minimum average reduction of area requirement was decreased as the yield strength of tubes submitted for inspection was increased. The values written into this specification were based on work done on Project NRC-38.

Since only about 1,300 forgings were submitted under Specification WVXS-88 before it was superseded by WVXS-95, the benefits derived from its use were small. However, it did result in the saving of about 2,000 tensile tests and 500 heat treatments. A report on the operating characteristics of Specifications WVXS-8 and WVXS-95 was prepared.[147]

Specification WVXS-95

This specification was developed for general application to all wrought gun tubes of various types and sizes for which yield strength requirements are above about 90,000 psi.

It is estimated that about the same number of tubes have been accepted under WVXS-88 and WVXS-95 as were accepted under U. S. Army Specification 57-105-1 formerly used. However, the aver-

[f] A batch lot consists of a group of tubes from the same heat which are tempered together.

age transverse ductility of the tubes accepted by the Army Ordnance Department as a result of using WVXS-88 and later WVXS-95 is higher, primarily because more tubes of low transverse ductility and fewer tubes of high transverse ductility were rejected by either WVXS-88 or WVXS-95.

The magnitude of savings in tensile tests and heat treatments which resulted from the use of WVXS-95 has not yet been estimated, but they are certainly very considerable.

Specification WVXS-131

This specification superseded WVXS-78, primarily because WVXS-78 did not specify an impact requirement, nor did it allow the transverse reduction of area requirement to change with the yield strength of tubes inspected. Both of these features were added to WVXS-131. The values written into this specification were based on information resulting from the NDRC work on Project NRC-38.

Specification 57-106A

Since January 1, 1945, U. S. Army Specification 57-106A has been in effect for the acceptance of steel forgings for cannon tubes. Its development resulted from the combined efforts of the Army Ordnance Department and NDRC investigations. Army Ordnance objectives were to write a single specification to cover the purchase of gun tubes which, if worn out, would fail by erosion, as well as gun tubes which, if worn out, would probably fail by progressive stress damage.

It is believed that U. S. Army Specification 57-106A adequately protects the quality of accepted gun tubes, provides an incentive for the producer to submit for inspection material of consistently high quality, and does not hamper production significantly.

3.2.7 Significance of Angular Fracture, Homogenization, and Upsetting in Relation to Transverse Ductility

Angular Fracture

At the start of World War II, the presence or absence of angular fractures was one basis for rejection or acceptance of gun tubes on the premise that angular fractures indicate low ductility. Since investigation of the significance of angular fractures revealed that they alone are not indicative of low ductility, it is believed that they should not influence decisions to accept or reject gun tubes.[148]

Homogenization

Studies of the effect of homogenization treatments on transverse ductility in forgings indicated that practical homogenization treatments are unlikely to improve the steel quality of forgings.[149]

Upsetting

An investigation of the effect of upsetting on transverse ductility in seamless tubes showed that upsetting raised average transverse reduction of area by about 2 or 3 per cent.[150]

3.3 IMPROVEMENT IN GUN STEEL INGOT PRACTICE

The seamless process for making gun tubes came into use early in 1942 primarily because an extremely large number of 40-mm M1 and 75-mm M3 tubes were required immediately by the Army, and it was not possible to supply forgings for such needs. Within a short time after tubes were first made by the seamless process, rejections owing to bore defects were excessively high. Actually, before the program for making 40-mm M1 and 75-mm M3 tubes was completed, approximately 10,000 tubes had been lost owing to bore defects and, unfortunately, about half of these were at least partially and often completely machined before the defects were found. The bore defects referred to here should not be confused with quench cracks, nonmetallic inclusions, or flakes. They usually are quite shallow and are believed to be internal ruptures caused by hot working.

As a result of the above situation, two projects were established, Project NRC-50 (OD-34-3), Control of Basic Open-Hearth Melting Practice for Manufacture of Wrought Gun Tubes, at the Timken Roller Bearing Company, and Project NRC-39 (OD-34-3), Improvement in Gun Steel Ingot Practice, at Carnegie Institute of Technology. One major objective common to both of these projects was the determination of the factors responsible for bore defects and the control of these factors so as to eliminate, or at least greatly reduce, bore defect losses. On Project NRC-50, steel making and processing factors were studied, while on Project NRC-

39, the work was limited to a study of ingot practices. Two other major objectives of the work done on Project NRC-39 were (1) to determine the effect of bore defects in gun tubes on tube performance, and (2) to supply information for the establishment of standards which would be useful in a quantitative study of the significance of each factor thought to influence the occurrence of bore defects, and for the assistance of the Army Ordnance Department in standardizing inspection procedures and in setting up specifications for the acceptance of 40-mm M1 and 75-mm M3 gun tubes made by the seamless process and containing minor bore defects. While such specifications are not at present available, it is known that both forged and seamless gun tubes containing minor bore defects have been accepted.

3.3.1 Relation Between Ingot Practice and Bore Defects

Investigations of the relation between each of a number of factors pertinent to ingot practice and the occurrence of bore defects failed to give leads as to what changes in practice were necessary to reduce bore defect losses in seamless gun tubes made from basic open-hearth steel.[151] However, it was observed that the maximum frequency of bore defects responsible for tube losses occurred in steel coming from a region of the ingot containing the cone of solidification, and this fact suggested that a change of ingot practice, which would lower the cone of solidification so that it would not appear, should reduce bore defect losses in guns. It was found that by slow cooling of the bottom of an ingot during freezing, the cone of solidification could be confined to a region of the ingot not contained in the gun tubes.[152] Fundamental studies of the solidification of steel ingots indicated the reasons why a slower cooling of bottoms should lower the cone of solidification in ingots.[153]

In plant experiments, the slow cooling of ingot bottoms during solidification was obtained by use of carbon insert insulators. In commercial practice, the use of carbon inserts would not be economical. However, if desired, a practice could be developed which would be economical and would at the same time accomplish the end sought. Such a practice used by one Canadian steel producer is the pouring of steel into molds set on refractory brick bottoms.

An experiment was planned to demonstrate whether, by slowly cooling the bottoms of basic open-hearth ingots used for seamless tubes, bore defect losses could be significantly reduced. However, this experiment was not tried for the following reasons:

1. At about the time the experiment was to be made, basic electric was substituted for basic open-hearth steel for the manufacture of seamless gun tubes. Furthermore, the probability of a subsequent reversal of this change was quite low, because basic electric steel was much more readily available than basic open-hearth steel.
2. The change from basic open-hearth to basic electric steel completely solved the bore defect losses problem, whereas cooling the bottoms of ingots more slowly could probably only cut bore reject losses in half at best.

3.3.2 Effect of Bore Defects on Performance of 40-mm M1 and 75-mm M3 Seamless Gun Tubes

During a critical period of World War II in 1942, when it was important that gun tubes should be produced and inspected as efficiently as possible, several hundred seamless tubes per month were being rejected. At that time little was known about the relation between bore defects and gun tube performance. Therefore, inspection standards were necessarily arbitrary. There were those who believed that practically all the tubes rejected for bore defects should have been accepted, and conversely, there were some who believed that the psychological effect of a visible bore defect in the tube of a new gun on the user of the gun justified the rejection of the tube regardless of its performance. In this connection it should be remembered that only a small percentage of the tubes rejected had bore defects so large as to be noticed readily except by a trained observer using a boroscope.

In order to obtain some information about the influence of bore defects on the behavior of seamless gun tubes, a number of such tubes were selected and subjected to firing tests.[154] Four 40-mm M1 and four 75-mm M3 tubes were used for the tests. It was estimated that three of the 40-mm and three of the 75-mm tubes would be classed among the worst 5 per cent of the total tubes rejected for bore defects. The

other tube of each size was rejected but contained only small defects and might even have been accepted by other inspectors. No effect on gun life and performance was noted in any case. In static detonation of projectiles in the region of the defects, the defects did not initiate brittle failures. However, the tendency for the defect to enlarge on progressive firing was greater, the nearer the defect was to the origin of rifling.

The observation that each of eight tubes rejected for bore defects had a normal life and gave a normal performance obviously does not justify the assumption that all the other 10,000 tubes rejected for bore defects would behave likewise. It is a fact, however, that the probability that such an assumption is true is definitely greater because each of eight drawn from the 10,000 showed a normal behavior. The assumption would be less probable if some of the tubes tested had behaved normally and some abnormally. In evaluating this probability, an effort was made to choose six of the worst tubes available. For this reason, it is likely that no more than 500 of the 10,000 or so rejected were as bad or worse than the six chosen.

Control charts of bore rejects indicated a definite lack of uniformity in bore inspection which seriously disturbs any correlation studies and which opens the question of the significance of inspection methods used for bore defects.

A study was made of bore defects and a series of pictures was obtained covering the usual range of defects found in practice. These pictures were discussed with Army Ordnance Department personnel, and a division yielding four classes of severity was agreed upon. This chart provides the means of classifying, by size and character, the type and possibly the severity of any particular defect.

A method of assigning a quantitative index of bore quality was developed, taking into consideration frequency of occurrence, size and character, and possibly severity as well as position of defect along the length of the gun tube. This rating was used to provide quantitative data on bore quality for statistical correlation studies. It also was suggested to the Army Ordnance Department for possible assistance as a means of description in gun tube inspection records.[155]

As a result of cooperative effort between the investigators on Project NRC-39 and the Erie Proving Ground, a rapid method for bore photography also was developed. This was used in practice at the Erie Proving Ground to photograph defects in bores before and after proof firing.

3.3.3 Classification of Bore Defects in Forged Tubes

A classification chart for bore defects in forged tubes similar to that developed for the classification of bore defects in seamless tubes was constructed. This was worked out in close cooperation with the Armed Services and is on file for future possible use.

3.4 CONTROL OF BASIC OPEN-HEARTH MELTING PRACTICE FOR THE MANUFACTURE OF WROUGHT GUN TUBES

The experience of the Timken Ordnance Company in processing for gun tubes about 140 open-hearth heats of steel from six steel companies, and in processing tubes from two piercing sources brought out marked differences in the etch quality and physical properties resulting from different melting and piercing practices. It was indicated that the type of inclusions found in the steel is related to the etch quality and the physical properties of the steel.

In order to study this problem, Project NRC-50 (OD-34-3), Control of Basic Open-Hearth Melting Practice for the Manufacture of Wrought Gun Tubes, was established in the laboratories of the Timken Roller Bearing Company in January 1943. The project was confined to studies of the melting variables in the making of steel to be used in making pierced or seamless gun tubes, as measured by the quality of the product as determined by mechanical and metallographic tests, acceptance records, etc.

As it was suspected that the melting practice employed in making the steel was one of the more important factors affecting gun tube quality, a statistical correlation was made of the numerous variables in melting and pouring practices in an attempt to determine the most satisfactory procedure. Correlation studies of melting and pouring variables with resulting etch and bore quality of gun tubes were conducted on 353 open-hearth heats of approximately 120 tons each. Of these, 142 were 40-mm heats and 211 were 75-mm heats. Complete logs of times, temperatures, additions, preliminary chemical tests, etc., were obtained from the producers on

each heat. Altogether, 8 different correlation studies were made, each on a different group of 40-mm or 75-mm heats.[156,157,158] The principal conclusions derived from these studies are as follows:[159]

1. Statistical correlation studies of 353 gun heats indicate that certain variables in melting and casting practice affect the etch and bore rejections.

2. The control of the oxidizing condition of the slag, particularly during the finishing period of the heat, has a pronounced effect on both alloy losses and gun quality. The more highly oxidizing and active slags cause greater loss of alloys and tend to produce poorer gun steel (as judged by increased gun rejections for macroetch and bore defects).

3. More frequently than not, heats with turnings in the charge result in higher gun rejections.

4. Two different types of melting practices employed by the same producer of 40-mm gun heats have been found to yield marked differences in resultant gun quality. Alloy losses and rejections are smaller on the heats melted under less oxidizing conditions.

5. FeCr additions to the bath are favored over Chrome-X additions to the ladle. Also, CaSi additions to the ladle are favored over FeSi additions to the ladle.

6. Control of tapping and pouring temperature is most important. A medium pouring temperature is most satisfactory. Skulled or cold heats are definitely unsatisfactory.

7. Heats poured into ingots with "C" and "D" hot tops tended to be better than those poured into clay-topped ingots. There is an indication that straight pouring is preferable to back pouring.

8. Exceptionally short and long holding times of heats after pouring are more frequently undesirable. Ingots of approximately 6,000 lb in weight should be held at least 1 hour before moving and preferably should be charged into the soaking pits within 4 hours after pouring.

The rolling and piercing practices were also suspected as having some effect on the quality of the guns. Studies of these practices were made,[159] with the following conclusions:

1. Heats which are direct rolled from ingots into 8 in. round piercing billets for 75-mm guns show better gun quality than those that are double converted into billets. Direct-rolled 40-mm heats, however, do not show any appreciable superiority over double-converted heats.

2. The direction of piercing a gun tube, whether with or against the original herringbone pattern in the ingot, has not been found to affect the quality of the gun tube.

3. Normal variations in both drawing temperatures of billets from the piercing mill reheat furnace and in electrical power consumed in the piercing of gun tubes showed no appreciable correlation with the resulting gun tube.

4. Piercing of 40-mm gun tubes with longer plugs is favored over shorter plugs. The greater surface area of the longer plug increases the amount of hot working on the inside diameter of the tube.

5. With the exception of the method of rolling ingots into billets, factors which tended to better 75-mm gun steel quality also bettered 40-mm gun steel quality.

6. The inherent quality of gun steel heats which is attained during melting and casting is by far the most important factor affecting gun tube quality. The most ideal rolling and piercing conditions cannot produce good quality guns from a heat which, for example, was poured very cold.

The second phase of the research program was the determination of the relation between the RAT and the several inclusion rating factors of good versus bad heats of steel.[158,159] Based on over 1,100 individual specimens from 123 heats of steel, a correlation was established between both quantity and type of nonmetallic inclusions and the RAT obtained in basic open-hearth Cr-Ni-Mo steel processed in 40-mm and 75-mm seamless gun tubes. Basing the inclusion rating on the Timken chart, for each unit of the rating chart in the direction of dirtier steel, the average or peak of the distribution curve decreases about 5 per cent RAT in 75-mm tubes, but less in 40-mm tubes. With the same total inclusion content, the stringer-type inclusion is more detrimental than the nonstringer type.

3.5 PREVENTION OF CRACKING IN GUN TUBES

A study of data from the manufacturers of gun tubes showed that in one year, September 1, 1942, to September 1, 1943, about 2,000 tubes of sizes varying from 40-mm to 8 in. were cracked during heat treatment. For this reason, in February 1944, Project NRC-80 (OD-34-3), Prevention of Cracking in Gun Tubes, was established at Carnegie Institute of

Technology in order to develop a suitable test for cracking susceptibility, to determine causes of quench cracking, and to propose practical steps to reduce losses from cracking to a minimum.

3.5.1 Development of Test for Cracking Susceptibility

A test was developed for determining the cracking susceptibility of gun tubes.[160] The basic properties of this test are provided by a series of disks cut from the bore of a gun tube and V-notched on the ID to induce cracking during a quench. The notched test disks are quenched in a jig in such a way that rapid cooling occurs on ID and OD surfaces only, that is, heat is abstracted from the disk wall radially. Cracking susceptibility is measured by an index value. As this value increases, the cracking susceptibility decreases. Notched disks from a portion of tube having a cracking susceptibility of ¼ in. would sometimes show notch cracks if the ID notches in the quenched disks were ¼ in. deep. (The root of notch is 0.012 in. and angle of notch is always 30 degrees.) Disks with 3/16-in. notches would rarely ever crack when quenched, and disks with 5/16-in. notches practically always would crack. The reproducibility of the test is probably good to within plus or minus 1/16 in. of the index value.

No significant correlation was found to exist between determined index values and percentages of tubes cracked per heat. The failure to find such a correlation probably resulted from inadequate sampling rather than from a lack of sensitivity of the test. When a treatment is used which causes all the material so treated to crack much less easily, then it is known that such a treatment raises the index values as determined in the cracking susceptibility test. For example, prebore quenching raised the ID index value determined by the cracking test and lowered cracking losses as determined by one company.

3.5.2 Causes of Quench Cracks

Quench cracks occur when tensional stresses are high enough to cause rupture. If such stresses are sufficiently high, cracks occur in steel of superior quality, and if steel quality is sufficiently poor, relatively low stresses cause cracking. Unfortunately, it is often quite difficult to determine whether a quench crack results from a change of stress pattern (heat treatment), poor steel quality, or a combination of both. (Other potential causes listed below as "remedies" also may be of considerable importance.)

Tentatively, it was concluded that cracking susceptibility is a heat characteristic. This means that even if heat treatment were held constant within the smallest limits of variation possible, cracking losses per heat would still be expected to vary markedly from heat to heat. The primary cause of the variation of cracking susceptibility among heats has not yet been discovered. Tubes not normalized tend to crack more easily than do those which are normalized, and tubes of relatively high carbon crack more easily than do those which have lower carbon content. At present, however, effects of normalizing and carbon content, within the range studied, are believed to be quite minor causes of cracking. Ingot bottom weakness (region of cone of solidification) is believed also to be a cause of cracking in gun tubes. Quenching from too high a temperature and quenching for too long a time showed evidence of causing quench cracks, but within the normal temperature and time ranges used in commercial practice, these factors too are only of minor significance from a practical point of view.

3.5.3 Remedies for Reducing Quench Crack Losses

The remedy to be applied for the purpose of reducing quench crack losses depends on whatever the major cause of cracking happens to be in the particular practice considered. This is not the same for each practice.

Quench-crack losses may be reduced by (1) prebore quenching, (2) using basic electric instead of basic open-hearth steel, (3) tempering as soon after the quench as possible, (4) using the lowest carbon content steel possible which will give the desired yield strength after the quench and temper, (5) choosing a composition which gives to steel little more than the hardenability desired and as high an *Ms* temperature as possible, (6) using a normalizing treatment before heating for the quench, (7) quenching from the lowest temperature possible

which will give desired properties after the quench and temper, (8) holding in quenching medium for optimum time, depending upon the gun type, size, and heat-treatment practice, (9) improving loading arrangement of tubes in batches to be quenched so that each tube is more uniformly quenched, and (10) improving the water circulating system.

In referring to remedies for reducing quench-crack losses, an attempt has been made to arrange them in order of effectiveness. It is believed that prebore quenching, which heads the list, is so effective and so generally applicable that its proper use in any practice is likely to reduce cracking losses to insignificance. One company lost four out of twenty-four 8-in. howitzers owing to quench cracks when the tubes were quenched simultaneously on both ID and OD surfaces before being tempered, but lost no tubes at all out of 172 when the bore was quenched for 2 minutes before ID and OD surfaces were quenched simultaneously.

Effects of each of the other variables seem to be beneficial when applied to one practice but of questionable value when applied to another practice. Considerable work remains to be done before the relative usefulness and applicability of the remedies mentioned above can be quantitatively evaluated. Work on this problem is being continued under an Army Ordnance Department contract.

3.6 HEAT TREATMENT OF GUN STEELS

It was made clear in the previously described studies that different heats of gun steel require different tempering temperatures in order to develop the required yield strength, and that each heat may have to be treated as a separate batch, rather than allowing tubes from different heats to be mixed, tempered at some arbitrary temperature, and individually tested with the result that many tubes have to be retreated. Thus, the selection of the proper tempering temperature and time for tempering each heat becomes an important step.

It is well known that equivalent tempering can be accomplished at a relatively low temperature for a long time or at a relatively high temperature for a short time. If the tempering furnace has good temperature uniformity and if the charge is so placed that all parts of it have equal ingress of heat, that is, if the charge is properly loaded into the furnace, the higher temperature and shorter time make for more rapid production. The degree to which the quenched steel is tempered is well indicated by the hardness.

For best properties in gun tubes (and in homogeneous armor), the steel must be quenched fully to martensite before tempering. If, during quenching, there is partial transformation at a relatively high temperature of austenite to ferrite and pearlite, or at a lower temperature to a range of acicular structures known as bainite, and if part of the austenite is thus used up in forming these structures, only a portion of the austenite remains to form the desired martensite at the low temperature at which this change occurs. On tempering, the desired tempered martensite (secondary troostite or sorbite, according to the tempering temperature) is interspersed with the ferrite-pearlite, or with tempered bainite, or both. These tempered nonmartensitic structures may have a hardness close to that of the desired tempered martensite, or they may be present in too small an amount to show up in the hardness determination. Their presence, however, is revealed by examination under the microscope. Such structures noticably depreciate the mechanical properties, and the notched bar impact resistance at low temperatures.

When nonmartensitic transformation products appear on quenching, the steel is said to be slack quenched. Failure to produce martensite results from too low a rate of cooling. The outside of a quenched gun can be chilled rapidly enough in the quench to make it martensitic, but, unless the austenite is sluggish enough to stand a lower rate of cooling without transforming to nonmartensitic structures, the center or even the outside partly transforms to these nonmartensitic structures. Plain carbon steel has nonsluggish austenite; in large sections, the center does not transform to martensite but rather to one or both of the nonmartensitic structures.

Carbon steel, therefore, is relatively shallow hardening to different degrees according to the carbon content. A drastic quench, such as water under pressure, brine, or other water solutions, cools the outside more rapidly than does oil, and slightly greater depth hardening can be obtained in carbon steels by water quenching instead of oil quenching. But even water-quenched carbon steel will not harden properly all the way through in sections corresponding to those of gun tubes, such as 40-mm,

75-mm, and larger. Hence, an alloy steel must be used in which one or more alloying elements are present to make the austenite sufficiently sluggish so that it does not transform to nonmartensitic structures. Such steels are more deeply hardening. As the section to be quenched increases, more alloy, and preferably two or three rather than just one alloying element, is required.

The hardenability of steel is evaluated by the now familiar Jominy test, in which one end of a cylinder is quenched by water under pressure, the other end not being touched by the water. After quenching, the distance back from the quenched end at which the desired hardness and structure have been obtained measures the hardenability of the steel. It is necessary to note that commercial evaluation of the Jominy test is often made on the basis of the distance from the end of the test bar at which 50 per cent martensite is obtained because at that percentage, in plain-carbon steels, there is an easily discerned difference in etching behavior. But 50 per cent martensite is slack quenching and the structure less desirable for ordnance purposes, compared to a fully martensitic structure. In gun steels a drop of five points in Rockwell C hardness is taken as an approximate criterion, but even this does not insure absence of large amounts of bainite.

Jominy hardenability testing for quenched hardness tells nothing about the structure or the fitness for guns or armor. The standard bar may show little drop in hardness clear out to the air-cooled end, yet that steel fails to harden at the center in the quenching of a heavy gun. It is necessary to evaluate alloy steels being considered for guns and armor in much more thorough fashion.

Chemical composition is only a means to an end and of no value in itself. Many combinations of elements and amounts of elements can be utilized equally well to avoid slack quenching. But, for conservation of available supplies of alloying elements, it makes a great difference whether a composition is chosen with just enough of readily available elements, or whether, through ignorance of the existence of substitutes, the composition calls for large amounts of critical or strategic alloys. Moreover, since the availability of different alloying elements varies from time to time and, under some conditions, may not be predictable, there is need not only for evaluation of substitute compositions that appear logical under the supply conditions of the moment but also for clarification of the methods of evaluation so that any other suggested composition can be promptly put through its paces to determine how well it avoids slack quenching.

3.6.1 Time-Temperature-Hardness Relations

To secure fundamental data on the thermal characteristics of gun steels from which improved heat-treatment cycles might be developed by gun manufacturers, Project NRC-36 (OD-34-3), Metallographic and Physical Properties of New Types of Gun Steels, was established at the University of Notre Dame du Lac in October 1942.

The initial phase of the investigation was a study of the time-temperature-hardness relationships of a typical gun steel. If one assumes that in actual practice the tempering time will be held constant and only the temperature adjusted to the needs of the particular heat, the determination of the correct temperature can be made by tempering for a standard time a properly quenched, long specimen in a furnace in which there is a temperature gradient covering the temperature range that is of interest, determining the hardness gradient thus produced, and from the results selecting the correct temperature to produce the required hardness. With two or more such gradient furnaces, operated for different tempering times, the time-temperature relations can be worked out.

However, it was found that it was not necessary to make the test quite so elaborate, since use could be made of an experimentally ascertained relationship by which, when the reciprocal of the absolute temperature is plotted against the natural logarithm of the reciprocal of the time, a straight line results for the observed points corresponding to any chosen hardness level. The straight lines for each hardness, that is, 40, 35, and 30 Rockwell C, are practically parallel. Then, if specimens are tempered at one fixed temperature but for two or more times, and if the results are plotted, the time-temperature-hardness relations are made evident. They can be expressed for each hardness level in terms of the intercept and slope of the plotted line. Once the slope is known for a given type of steel, a single specimen from each heat can be tested at one time and temperature, the result plotted, and a straight line drawn parallel to the standard slope. Thus, for example, by tempering specimens at 1175 F for 1 hour, it was shown that to produce the specified hardness

for 40-mm tubes for four different heats of the same type of steel would require tempering temperatures of 1150, 1160, 1170, and 1180 F. These would then meet the hardness specifications exactly. If all had been tempered at the average temperature of 1165 F, the heats that needed 1150 F and 1180 F would not have been tempered correctly.[161]

This test method for determining the correct tempering temperatures for fully hardened and tempered gun tubes was adopted by the Timken Roller Bearing Company, a manufacturer of seamless gun tubes, and resulted in the development of an improved heat treating practice. In this practice, which was fully automatic and continuous, the only variable which could be adjusted easily was the tempering temperature. By the use of this test method, the optimum tempering temperature of each heat of steel was employed. This resulted in a substantial decrease in the number of rejections and a corresponding increase in production of seamless gun tubes.

To extend the use of this method of predicting optimum tempering temperatures to other types of gun steels being used, Project NRC-85 (OD-34-3), Time-Temperature-Hardness Relations in New Gun Steels, was established in June 1944 at the University of Pittsburgh.

This investigation covered studies of eight selected gun steels, one of which was similar to that upon which the original test was developed, as well as an armor composition which was suggested by Watertown Arsenal for a comparison with the gun steels.

Earlier findings for steels of 0.30 to 0.60 per cent carbon were corroborated.[162,163] A lower carbon steel behaved somewhat differently, but in the carbon range used in most guns and armor, the general patterns of behavior on tempering were so similar that predictions as to temperability, and the effect of alloying elements upon it can be made with considerable accuracy and with a minimum of experiment.

These investigations of time-temperature-hardness relations demonstrated principles applicable to any heat of that steel, or to any heat of any other steel that shows complete martensitic hardening on quenching in the sections obtaining in the gun tubes being made.

3.6.2 Slack Quenching

Because of the very different behavior of gun tubes with slack-quenched and tempered structures and the limited knowledge of these structures, the investigation of the heat treatment of gun tubes at Notre Dame, Project NRC-36, was extended to include a systematic study of the tempering characteristics, metallographic structures, and physical properties of gun steels with slack-quenched structures. It has been found generally that slack-quenched gun tubes have inferior physical properties, especially with respect to impact strength. Probably the most important information relevant to this problem is the time for initial decomposition at any temperature and the nature of the product or products of decomposition at that temperature. Since a systematic attempt to study slack-quenched structures must be preceded by a thorough knowledge of the S-curve for the steel under consideration, S-curves for ten typical gun steels were determined with particular emphasis on the temperature of martensite formation.[161]

The behavior of a steel in respect to retention of austenite is mapped traditionally by the S-curve. This is obtained by the isothermal method, that is, the steel is heated until it becomes austenitic, then immersed in a fused salt or fused lead bath, held there at a definite temperature for a definite time, and then quenched in order to transform to martensite the austenite not previously transformed to ferrite, pearlite, or bainite. The piece is then examined for hardness and structure. With enough data taken at various different times of residence at temperature, a behavior chart is made, showing the range of time and temperature the austenite can endure without changing over to a nonmartensite product. This chart gives a correct picture for the behavior under just such isothermal conditions, but the picture is incorrect for quenching conditions where the temperature is continually dropping. Empirical corrections have been suggested, but since these are not generally applicable with any degree of exactness, the use of ordinary S-curves in evaluating gun steels has distinct limitations. In the experimental examination of methods of evaluating the true slack-quenching behavior, it appeared that bainite is formed in two stages and that austenite retained with it is persistent, that is, resists decomposition on tempering after quenching, but on cooling from the tempering temperature it may transform to fresh, hard, brittle martensite.

In this investigation it was tentatively suggested that the presence of this brittle, untempered martensite, as well as the recognized deleterious presence

of ferrite or bainite, is partially responsible for much of the poor mechanical behavior of a slack-quenched structure. If this is true, a second tempering to temper this late-formed martensite should help.

In 10 steels of such hardenability as to be of some interest for guns, this same two-bainite-reaction phenomenon was noted. All the steels contained 0.30 to 0.40% C. Some of them had 1½% Mn, 2 to 2.75% Ni, 0.60 to 0.80% Cr, 0.25 to 0.40% Mo, 0 to 0.10% V. Others, with no or low nickel, contained 0.90 to 1.00% Cr, 0.20 to 0.55% Mo, 0 to 0.12% V. One had no Ni, 1.00% Cr, 1.00% Mn, 0.50% Mo, 0.10% V. Regular S-curves were drawn for these on the basis of isothermal holding and resultant structure and hardness, and dilatometer tests. Some information was obtained on the speed of the first and second bainite reactions as a function of temperature.

This work was insufficient to evaluate the possibilities of the steels as gun steels, inasmuch as to bring out those possibilities would require slack quenching, double tempering, and determination of mechanical properties at the time maximum attention had to be directed to guns requiring thorough quenching. The work indicates that evaluation on the basis of S-curves, as ordinarily obtained, may eliminate steels that, heat treated in the light of the evidence obtained, would produce good quality guns and be economical of strategic alloying elements.

3.7 FATIGUE STRENGTH OF GUN STEEL

At the request of the Army Ordnance Department, the Metallurgy Section of the former Division B, NDRC, established Project B-189 (OD-34-10), Fatigue Strength of Selected Gun Steels Under Combined Stress, at the University of Michigan in October 1941. The program covered combined-in-phase bending and torsion fatigue tests. A testing machine designed for a speed of 3,600 rpm was constructed and a pilot test was made on SAE X4340 steel.[164] The tests were based originally on the importance of determining characteristic relationships at the endurance limit (10,000,000 cycles) and, for this reason, the data available for the determination of any definite trend at higher stresses are insufficient.

Since the results of this study were highly uncertain and since it appeared that the effort could be applied to problems of more urgent importance in the war effort, the project was terminated in September 1942, and the testing machine was shipped to Watertown Arsenal for possible future use.

The few data obtained on this investigation may have a bearing on the multidirectional stress problems met in the ship failure problem, discussed in Section 6.2.3 of this report. The results tentatively indicated that when repeated bending is predominant failure tends to be in the normal brittle fashion of the ordinary fatigue test, but changes to a ductile failure when repeated torsion is predominant.

3.8 DEVELOPMENT OF NEW GUN STEELS

In February 1944, the Research Group, Subcommittee on Gun Forgings, Ferrous Metallurgical Advisory Board, Army Ordnance Department suggested the establishment of Project NRC-81 (OD-34-3), Development of High-Strength Gun Steels. Although the OSRD contract was placed with the Vanadium Corporation of America, the research program was a cooperative effort. The heats of steel, the compositions for which were selected by the War Metallurgy Committee Project Advisory Committee, were made by the Midvale Company, the specimens were prepared and heat treated by the Vanadium Corporation of America, and the tests were made by the United States Steel Corporation Research Laboratories, by Watertown Arsenal, and by the Vanadium Corporation of America.

The purpose of the search for new gun steels was to find a steel reasonably amenable to regular steel-making processes, forging, etc., by which the yield strength now consistently obtained in 75-mm guns 140,000 to 170,000 psi, and in 76-mm guns, 150,000 to 180,000 psi, might be reached in larger sizes.

The logical way to reach this goal is through the development of a deep-hardening steel with an S-curve such that bainite is avoided and martensite produced at the center of the section of quenching.

The same approach was taken here as in the armor projects[119,122] discussed in Section 2.3 of this report, that is, systematic variation of composition and determination of the resultant hardenability and S-curves. In the gun steel work, the level of carbon content was higher than that in the armor projects, and only the ordinary alloying elements, manganese, nickel, chromium, molybdenum, and vanadium, were utilized. The study of boron additions was to be deferred until the preferable

combinations of the other elements were ascertained.

Attention was directed especially to the crucial part of the S-curves, that just above the temperature of the start of martensite formation *Ms,* at which the too early formation of bainite would introduce undesirable properties. Among other treatments, isothermally treated notched bar impact specimens that had been held for varying times just above the *Ms* point were quenched and tempered, cooled, and tempered back to 40 Rockwell C. This gives an opportunity for retained austenite to transform to martensite on cooling from the first tempering, and this martensite in turn to be tempered. The impact values on specimens so treated serve as an indication whether bainite has been produced in the isolthermal treatment. This simulates the quenching cycle of the so-called "martempering" process which holds a heavy section just above the *Ms* point for temperature equalization before quenching.

Jominy curves, S-curves, *Ms* temperatures, and impact values after the treatment discussed above were determined and reported[165,166] for some two dozen compositions, some of which showed promise. The work was of a preliminary nature, aimed to pick out the most promising lines of attack. It will need to be carried further and ultimately to be supplemented by a study of boron additions to the more promising compositions.

The basic metallurgical data such as Jominy hardenability curves and S-curves for the SAE and the NE steels that serve for the smaller sections made from heat-treated steels are available in published literature, but no published survey of steels for use in heavy sections compares in completeness with the studies of heavy armor and large guns made in these NDRC projects, incomplete and preliminary as they still are.

It is understood that research of this nature will be continued by the Army Ordnance Department in the research laboratory at Watertown Arsenal.

3.9 PRESENT STATUS OF RESEARCH ON GUN STEELS

Further work was needed on several phases of the NDRC research program on gun steels when the principal projects were terminated in June 1945 in accordance with the NDRC demobilization plans. This was recognized by the Office of the Chief of Ordnance, and arrangements were made to have the projects conducted at Carnegie Institute of Technology transferred to direct Army Ordnance contracts. The projects concerned are Project NRC-38, Improvement in Wrought Gun Tubes; Project NRC-39, Improvement in Gun Steel Ingot Practice; and Project NRC-80, Prevention of Cracking in Gun Tubes. These continuing phases of the gun steels research program were mentioned as each topic was discussed in this report.

Other work also seems to be desirable. Cracking is still a major factor in rejection, and the causes have not been determined nor have methods been devised to determine adequately the propensity toward cracking.

The possible beneficial effect of double tempering of steels with retained austenite should be explored further, since it might be an important factor in the selection of alternate steels.

Search should continue for alternate steels that are not too prone to injury on slack quenching and yet do not call for large amounts of strategic alloys; and, since the supply of any one alloy may fluctuate widely, different alternates should be worked out and comprehensive data put on the shelf to be taken down as need arises. Regardless of the alloy situation, compositions or treatments less prone to cracking on quenching and producing better toughness at high yield strengths are needed.

3.10 INDEXING OF DIVISION 18 REPORTS ON GUNS AND GUN STEEL

To make the research information in the many Division 18 reports on guns and gun steels more readily available and to enhance the usefulness of the reports, the librarians of the Research Information Division of the War Metallurgy Committee prepared a comprehensive index of all of the reports issued. This index[167] provides a subject index of the information obtained on the topics studied and a listing of the projects with the serial numbers of the reports submitted on each.

Chapter 4

AMMUNITION

4.1 INTRODUCTION

FIVE INVESTIGATIONS were conducted on materials for three components of ammunition: armor-piercing shot, cartridge cases, and driving bands. These studies were made at the request of the Office of the Chief of Ordnance and were but phases of the extensive ammunition programs being conducted by the War and Navy Departments.

4.2 ARMOR-PIERCING SHOT

As one phase of the alloy conservation program, a study was made of the use of the special nonalloy steels for the manufacture of armor-piercing capped shot to obviate the use of critical alloys. Since the use of special addition agents in plain carbon steels had been investigated by the Buick Motor Division of General Motors Corporation during the period of automotive production and had been applied successfully in the manufacture of various high duty parts, Project NRC-37 (OD-107), Investigation of the Use of Special Non-Alloy Steels for Armor-Piercing Capped Shot, was established at Buick.

The initial phase of this research program was confined to studies of steels treated with additions of Grainal (a complex deoxidizing agent containing vanadium, calcium, aluminum, and boron) replacing the usual alloying elements used for the manufacture of the WD-4150 modified 37-mm projectile. Various modifications and heat treating cycles were tried to determine which would produce a projectile having the best ballistic properties. The tests conducted on the steel from which each lot of projectiles was machined included chemical, tensile, Izod impact, Jominy hardenability, grain size, and inclusion counts. Samples of each completed lot of projectiles were examined for hardness pattern and microstructure and then submitted to the Aberdeen Proving Grounds for ballistic tests. The results indicated that satisfactory projectiles could be made of Grainal-treated nonalloy steels as the performance of two of the experimental lots exceeded that of the standard projectiles with which they were fired.[168]

The second phase of the research program was concerned with the development of a shot with superior ballistic properties from both nonalloy and alloy steels. One of the most significant difficulties encountered in the performance of 37-mm AP projectiles was the destruction of the projectile ogive upon impact. This was not so common with AP projectiles of larger calibers. Various modifications in processing, together with a number of different steel compositions, were tried in an effort to improve shot performance. Among these were the carburization of the ogive, austempering, design changes of the projectile body and cap, and refinement of the induction base draw and hardening cycles. A projectile with the rough contour of the ogive formed by forging which had passed through a 1½-in. face-hardened armor plate intact was examined, and a lamellar pattern in the hardened zone was found. This disclosure subsequently influenced all experimentation on the project. The investigators believe that the most significant development of the work on this phase of the program is the importance of the heat treating cycle. The ballistic performance of each of six experimental lots was outstandingly successful. These lots were composed of three steels of widely different compositions, each of which had been heat treated with special reference to the particular material involved.[169]

It appears that a boron-treated simple manganese steel NE-9262 boron-treated NE-9465, or other steels of similar hardenability, will serve equally well for the fabrication of AP shot, structure and hardness gradient being the important factors rather than composition. As the work on this project was limited in scope, it should be correlated with the mass of information obtained in the production and testing of the millions of AP shot of this and other sizes produced by various contractors who applied various types of heat treatment to secure the desired graded hardness.

4.3 CARTRIDGE BRASS

Three investigations relating to stress-corrosion cracking of cartridge brass were undertaken at the request of Frankford Arsenal. These covered (1) the

prevention of stress-corrosion, (2) the detection and elimination of internal stresses contributing to stress-corrosion, and (3) the effect of volume changes associated with phase changes.

4.3.1 Stress-Corrosion

In the forming of brass cartridge cases, internal stresses are introduced. Unless these stresses are completely relieved, a residual stress remains. Under some corrosive conditions arising from the powder inside the case or from the atmosphere outside, stress-corrosion cracking may occur which spoils the case. Old ammunition which has been in storage may become useless because of this. This phenomenon was at one time referred to as season-cracking, but with subsequent knowledge that many alloys crack under corrosive conditions which tend to attack grain boundaries when the alloy is under tensile stress (either residual internal stress or externally applied stress), the term stress-corrosion has been adopted. The problem is as old as the brass cartridge case, but it is still a continuing problem.

Prevention of Stress-Corrosion

Since stress-corrosion cracking requires both stress and corrosion, avoidance of either factor, stress or corrosion, will prevent it. Of course, prevention of any sort of corrosion, whether it produces cracking or not, is worth while.

Under their control number OD-25, the Office of the Chief of Ordnance requested NDRC to investigate a variety of coatings to supplement Frankford Arsenal's work on organic coatings. Project NRC-27, Prevention of Stress-Corrosion Cracking of Cartridge Brass by Protective Coatings or Surface Treatments, was established in the research laboratories of the New Jersey Zinc Company.

Since cartridge brass is composed of copper and zinc, electroplating the case or the brass strip from which it was formed with one of these metals is a possible method of protection.

To study the protective value of these and other coatings, tensile specimens of stress-relieved cartridge brass strip were dead-weight loaded to 15,000 psi and subjected at 99 F to an atmosphere of 82 per cent relative humidity containing 90 per cent air, 20 per cent ammonia gas, and a small addition of carbon dioxide. This is a standard accelerated test, the results of which correlate well with actual service exposures. Unprotected specimens break in 5 hours under the test conditions.

Copper is attacked by ammonia under these conditions, but there was a possibility that the attack could be slowed down. However, the results of the investigation indicated that thin coatings of copper give no benefit and a coating 0.0012 in. thick only delays failure about 50 hours, whereas a zinc coating of the same thickness delays failure about 470 hours. Even thin coats of electroplated zinc prove effective and, moreover, extend electrochemical protection to bare areas where the zinc coating had been scratched away. The effectiveness is proportional to the thickness of the zinc coating. The corrosive atmosphere slowly removes zinc, but the zinc exercises protection as long as even a thin coating remains and as long as bared areas from which zinc has been completely removed are not too large. Thick zinc coatings protect larger bare areas than thin ones.

The applied stress is not a major factor. Stresses ranging from 10,000 to 24,000 psi do not affect the breaking time of zinc-coated specimens. That is, as long as the coating prevents corrosion of the brass, stress-corrosion cracking does not occur. After corrosion of the zinc coating exposes a brass area too large for electrochemical protection to be effective, the brass behaves as it would without zinc, that is, brass containing internal stress fails rapidly while the stress-relieved material stands up.

Zinc slowly diffuses into brass at somewhat elevated temperatures. Zinc coatings of various thicknesses allowed to diffuse for two months at 203 F were found to afford as much protection as those without the diffusion treatment. Hence, diffusion of zinc on storage at high atmospheric temperatures will not decrease the protection. No zinc coating other than that applied by electroplating was found satisfactory. Metal sprayed zinc does not adhere unless the brass surface is roughened more than can be tolerated, and sherardized coatings are less protective than electroplated ones of equal thickness. Moreover, the sherardizing process requires temperatures above those used for stress-relief annealing.

Under the test conditions where unprotected brass specimens break in 5 hours, those coated with 0.0003 in. of zinc stand up 120 hours; with 0.0006 in., 240 hours; and with 0.0013 in., 500 hours. Thus, the life increases linearly with thickness of zinc coating.

The electrochemical protection afforded by the

zinc is noteworthy. Small scratches through the zinc do not materially decrease the life, while the life of a test specimen with a zinc coating 0.003 in. thick and with a bare space 1/8 in. wide, freed from zinc, falls only to 100 hours. A further increase in life results when the zinc coating is "Cronak" treated, that is, dipped in a solution that produces a thin film of slightly soluble chromate on the surface. In the presence of atmospheric humidity, this film supplies a chemical inhibitor against corrosion. The filming does not destroy the electrochemical protection of areas scratched or bared after the filming treatment. Brass coated with 0.0003 in. of zinc, chromate filmed, then scratched to bare brass, will last 175 hours.

Instead of applying the zinc electroplate to the completely formed cartridge case, manufacturing would be simplified if the plating could be done at an earlier stage. On the basis of preliminary experiments, plating of fourth draw pieces with 0.0003 in. of zinc, with the final anneal converting the zinc to an alloy by diffusion into the brass, and the possible flaking off of some of the alloy, would still result in somewhat reduced, but still very long, life. This feature should be studied more completely if zinc plating is to be adopted.

Zinc, or zinc-coated brass, is not appreciably attacked by various propellent powders, even on storage at 122 F for a year. A comparative test of a duration of 1 year was inconclusive in that the unstress-relieved, unplated cases used for comparison with plated ones did not themselves show season cracking in this period of exposure. At any rate, in addition to the fact that the zinc-coated cases did not crack, neither did they show visible corrosion.

Since the zinc coatings and coatings with the chromate treatment proved effective even when scratched, zinc, zinc oxide, and zinc chromate were used as pigments in several types of lacquers. The lacquer thickness was about 0.0015 in. The testing technique was the same as that on the zinc-coated specimens. Zinc oxide or zinc chromate alone had little effect, but zinc dust (actually a mixture containing 80 per cent of zinc and 20 per cent of zinc oxide) did show considerable protection, and the scratched specimens behaved about as well as the unscratched. A variety of other pigments and a mixture of 80 per cent zinc dust and 20 per cent of plaster of Paris in a urea-formaldehyde vehicle failed to do very well when the lacquer was scratched, but zinc sulphide in this vehicle (coating 0.0011 to 0.0012 in. thick) showed marked protection. However, it did not do so in a phenolic resin vehicle.

In urea-formaldehyde, bismuth trisulphide or lead sulphide was even more effective than zinc sulphide, in 0.0010 to 0.0020 in. thickness. However, none of the three useful sulphides gave satisfactory performance when the pigmented urea-formaldehyde coating was less than 0.0010 in. thick. This is three times the thickness that can be allowed on cartridge cases.

Several thin organic coatings, if continuous and not scratched, prevent ammonia stress-corrosion. Among these are a wax known as Puritan Cartridge Coating Compound and an unmodified phenol-formaldehyde coating. None of these exert protection when scratched through.

Another possible way of minimizing stress-corrosion would be to put the surface in compression, as by shot-blasting, a method known to be effective in combating fatigue failures. Slight mechanical working by hand burnishing or scratch brushing, as well as shot-blasting, in some cases showed minor improvement in life, but much less than is produced by a very thin coat of zinc. Since the commercial application of shot-peening was considered difficult to apply to cartridge cases, particularly to the interior, its possibilities were not further followed up in this project. It is possible, however, that the application of 150,000 psi in tension in the test method used more than neutralized the surface compression stresses introduced by shot-peening.

This project clearly demonstrated the efficacy of thin electroplated zinc coatings and the electrochemical protection afforded to scratched areas. The results of the work are summarized in the final reports,[170,171] while the details are covered comprehensively in five progress reports.[172,176]

Evaluation and Elimination of Residual Stresses

Stress-corrosion cracking in cartridge brass is avoided if there is no corrosion or if there is no stress. The project discussed above related to prevention of corrosion. Another project, relating to the evaluation and elimination of residual stresses, was established at Lehigh University by the Metallurgy Section of former Division B of NDRC. This was Project B-220 (OD-25), Residual Stresses in Cold-Drawn Non-Ferrous Alloys.

The distribution of internal stress can be approximately ascertained by machining or splitting off layers and noting the dimensional changes resulting

from the removal of this material. Another way is by use of X-ray diffraction methods which can be applied to measure the interplanar spacings between atoms in the metallic crystal. In strain-free material this spacing has a fixed value. If compressive stress is present, the atoms are squeezed together and the spacing is smaller. If tensile stress is present, they are pulled apart and the spacing is larger. Therefore by measuring the spacing in a stressed area and comparing it with the value determined for the normal lattice, the existing stress can be evaluated.

The X-ray measurement can be made accurately only on the surface. However, by etching away successive surface layers and determining the surface stress each time, the redistribution of stress, resulting from removal of material is shown. From this redistribution, the original stress conditions prior to etching can be calculated. The method offers possibilities of greater precision than can be obtained by measuring dimensional changes.

Extension and refinement of the X-ray method applied to measurement of stresses in cartridge cases was desired by Frankford Arsenal, and Project B-220 (OD-25) was set up with these aims in view.

The production methods used in making cartridge cases generally result in compressive stresses at the surface. The higher the compressive stress and the greater the depth to which compressive stress extends, the more the resistance to stress-corrosion cracking, which results partially from tensile stress. Tensile stress, to balance the surface compressive stress, will occur below the surface. When corrosion penetrates the surface locally and gets down to material that is under tensile stress, stress-corrosion cracking will occur.

X-ray measurements applied to cartridge cases processed in different ways can reveal the stress distribution at each step and thus point the way toward modifications in processing methods which could remove or delay the danger of stress-corrosion cracking. The effect of different methods of pickling, producing rough or smooth surfaces that hold or do not hold lubricant in the next draw, die angles of the drawing die, etc., were examined. The effect of variation in composition (percentage of zinc) and of a zinc gradient due to volatilization of zinc from the surface had to be taken into account.

Because of the varying amount of cold work at different locations in the case, the varying thicknesses, and the variation of restraint upon the walls, which is high at the base and low in the body, the stress conditions vary considerably over the length of the case, making measurements at several locations necessary. The X-ray method examines only a small spot and thus is a more selective measure than are dimensional measurements.

The equipment and technique for X-ray measurement of surface stresses on the outside and inside of caliber 0.30 cases are fully described in the reports, and the results of many variations in processing upon the magnitude and distribution of stresses are recorded.

In general, the method gives useful and illuminating results, but in the ammonia-cracking test, body cracks occur that could not be predicted by the X-ray studies. This anomaly needs further study. Final reports[177-182] have been used on many phases of the problem, but the work is being continued under a direct contract with the Ordnance Department.

Effect of Density-Volume Changes Associated with Phase Changes

A possible cause for susceptibility to intergranular corrosion, as well as for the splitting of cartridge cases during forming, might be the initial presence in the cake from which the strip is rolled for forming of some beta (zinc-rich) phase in the alpha (copper-rich) phase.

The beta phase exists in the center, which is the part last to freeze, of most large cakes. It is diffused and transformed to the alpha phase by annealing. If the annealing is insufficient, however, diffusion will not be complete and a laminated structure will result revealing ghost or phantom lines where the beta phase occurred. The brass may show a finer grain along the contact line, and grain size is important in the fabrication of brass.

It was suspected that the transformation might leave voids at the original beta location because the beta phase is very slightly less dense than the alpha phase, that is, it occupies more volume.

To investigate this problem Project NRC-62 (OD-117) was established at the University of Minnesota in July 1943. It was shown that (1) the volume changes which result from transformation of the beta phase to the alpha phase are extremely small and do not cause voids, and (2) proper annealing, even of cartridge brass with zinc content at the high zinc end of the specification, will prevent any trouble that might arise from the initial presence of beta.[183]

4.4 DRIVING BANDS

Shortage of copper forced Germany to find substitutes for copper or gilding metal driving bands. Under Project NRC-32, Examination of Enemy Matériel discussed in Chapter 8, several German driving bands were examined. The first step in copper conservation was the use of a bimetal band, with copper on the outside, soft iron on the inside. Instead of being made as a complete ring, the bimetal band was made in sheets, presumably by hot-rolling a slab of iron surmounted by a slab of copper. Strip of the proper dimensions was cut from the duplex sheet and forced into a knurled and undercut groove. The ends were so forced together that the joint could scarcely be found by visual inspection. Despite this joint, the band functioned properly.

In the duplex band, the iron extends nearly to the surface of the projectile; the raised part which contacts the lands and grooves of the gun is copper. This saves approximately half the copper that would be required by a solid copper band.

The duplex band was used as a first-step conservation measure but was later replaced by all-soft-iron bands, used only to a limited extent, or, more commonly, by sintered-iron bands. These were formed in ring shape from metal powder. This powder was derived not from very pure iron, but rather from scrap low-carbon steel much like that used by the Germans for cartridge cases. The compacted ring was lightly sintered, impregnated with oil to prevent rusting, and pressed into the undercut, knurled groove. After pressing in, it still had some 20 per cent porosity, which permits easy deformation. The metal-powder bands in place appear very brittle when they are being pried off, but they withstand the compressive and shear stresses caused by being engraved by the lands and grooves in driving the projectile. They have become the German standard for projectiles up to 150 mm and have replaced the duplex copper-iron band.

It was suspected that the sintered-iron band would wear the gun tube more than the copper of the duplex band. On the contrary, a captured German document, (OTIB 155 D338, August 1, 1943) shows curves of increase in the diameter of lands at the beginning of rifling of a 105-mm light field howitzer 18 (over 8,000 rounds), with projectiles equipped with bimetal and with sintered-iron bands.

At 5,000 rounds, the land diameter had increased 0.7 mm with the bimetal band, but only 0.2 mm with the sintered-iron band. Increases of 0.8 and 1.0 mm at that location are shown in another curve as having brought the 105-mm light field howitzers to the ends of their useful lives. Extrapolating the first pair of curves, it would appear that the use of the bimetal band on the projectiles would give the howitzer a life of 7,000 to 10,000 rounds, while the sintered-iron bands would give double that life. A definite statement that the life of this howitzer is doubled with the sintered-iron band is also made in this document. In the course of other comments in this document, reference is made to the great pressure exerted by the bimetal band. The sintered-iron band is also preferred to the bimetal because there is no coppering of the bore. The film of iron deposited is so slight as to be of no importance.

From this evidence it would appear that the complete replacement of copper in the driving band by sintered iron might, from the performance point of view as well as from that of conservation of copper, be more fruitful than partial substitution by the bimetal band. The Army Ordnance Department has been experimenting with various sintered, metal-powder bands.

However, the suppliers seem to have sought to secure density and freedom from porosity, trying to make the product as much like a solid iron band as possible, whereas the performance of the German band is probably due to its porosity. An inspection team in Germany after cessation of hostilities found records comparing solid, soft iron bands, which were in limited use, with sintered bands, much to the advantage of the porous band in regard to barrel wear. It was also reported that the iron powder was made by grinding up low-carbon steel scrap, rather than by electrolysis or by the reduction of the oxide. The compositions of German steel cartridge cases and powdered iron bands were so similar that it appears likely that scrap cartridge cases or trimmings from cartridge cases were the raw material.

However, until the German data on wear with the sintered band are confirmed by American tests, the duplex band in which the operating face is copper seems a logical first step in conservation.

At the request of the Bureau of Ordnance, Navy Department, Project NRC-60 (No-159), Bi-Metallic Rotating Bands for Projectiles, was established by NDRC at the General Electric Company Research Laboratories. The objective of this project was to

investigate methods of producing a satisfactory bond between copper and steel by means of alloys and a study of the mechanical properties of bimetal driving bands for 40-mm naval projectiles.

German methods of production could not be applied, for the instructions from the Bureau of Ordnance were to produce bimetal rings, not strip, in order to retain the usual technique of banding. The possibility that bimetal tubing, to be cut into bands, could be made by centrifugal casting had been explored by the U. S. Pipe and Foundry Company under Project NRC-26 (discussed in Section 7.2.5 of this report). It was not found feasible to cast iron inside copper owing to the respective melting points, although a copper-lined iron tube could have been produced.[184] Other casting methods tried were unsatisfactory, so recourse was taken to bonding a copper tube to a steel tube placed inside it.

Various brazing solders were tried, along with various methods of heating the nested pair of tubes. Zinc was selected as the best bonding agent since it alloys with both iron and copper at a relatively low temperature. Metal spraying appeared to be the best method of applying the zinc.

SAE 1010 carbon steel tubing 1.715-in. OD, 0.30-in. wall, surface ground, was spray-coated with 0.006 in. of zinc and slipped inside a 2-in OD, 0.125-in. wall copper tube. The composite tube was drawn through a single die to 1.846-in. OD, 1.570-in. ID, over a plug. This resulted in a composite tube with wall thickness of 0.103 in. copper, 0.005 in. zinc, and 0.130 in. steel. After various methods of heating in an attempt to melt the zinc and produce bonding, 8-in. sections were heated 20 to 25 minutes in an electric muffle furnace operating at 1740 F. This produced some volatilization of zinc as vapor and did not bring about 100 per cent bonding. At least 75 per cent of the area was bonded and the unbonded areas were uniformly distributed. This partial bond was appraised as stronger than the grip on the knurling of the shell, and hence adequate for the purpose. A lot (Lot 1) of 34 shells was provided with bimetal bands so made. Banding was performed as usual and without trouble.

To produce more complete bonding, another lot (Lot 2) was prepared in the same manner, but heated for bonding in a hot press consisting of a pair of carbon blocks shaped circumferentially to fit the OD of the composite tube. Current was passed through the assembly, heating it to 1740 F. After about 6 minutes heating, while the tube was hot, slight pressure was put upon the outside of the tube, the current was cut off, and pressure was maintained until the tube was cool. Copper is soft enough at 1740 F so that a tight bond is obtained. In production, this external pressure probably would be applied by hot drawing through a die. Lot 2 contained 62 shells provided with bimetal bands made by the hot press method.

Lots 1 and 2 were fired by the U. S. Naval Proving Ground at Dahlgren. The Dahlgren report stated that examination of Lot 1 showed discontinuous bond and a possible tendency to strip, while Lot 2 was sound, with no indication of deficiency in ductility or strength. Apparently, both lots functioned properly in the firing tests.[184]

Since the results obtained with the naval 40-mm projectile were so successful, work was done also[185] on the production of driving bands for the naval 3-in. projectile and the Army 37-mm projectile. The attempts to produce satisfactory driving bands for the naval 3-in. projectile by the above method were unsuccessful because the hot press equipment used for the purpose did not have sufficient electrical capacity to effect rapid heating and to attain the temperature required to produce the alloy bond. A lot of Army 37-mm driving bands was shipped to Frankford Arsenal for firing tests. The results of these tests have been reported by Frankford Arsenal.[186]

It was concluded that the process could be used to conserve copper. The cost of production would, of course, be above that of an all-copper band, so that the process would not be economical when copper is available.[184]

It would be logical to extend this work to bimetal strip rather than confine it to bimetal rings, since the German experience shows strip bands to be effective, and their production would be much simpler.

A U. S. Naval Technical Mission in Europe concluded,[187] on the basis of documents searched and interrogation of German personnel, that (1) the copper-clad steel band will give almost as good service as a copper band; (2) the sintered-iron band was the best substitute for copper bands, although its development was not as yet complete; and (3) soft iron bands were not so satisfactory as the copper, copper-clad steel, or sintered-iron bands, although they were a substitute for sintered-iron bands in high-velocity and large guns for which the sintered-iron band had not proved to be satisfactory. The Germans

realized that the investigation of the sintered-iron band and rifling design was by no means complete.

In view of the evidence indicating that German experience evaluated the porous sintered-iron band as the best substitute for solid bands in some types of guns, at least on the score of barrel wear, further study of driving bands obviously should begin with the duplication of porous band and its trail in American guns. That band seems so good in performance, as well as on the score of complete observation of copper, that further effort on the duplex band could at least be deferred until test results are available.

Chapter 5

METALS FOR HIGH-TEMPERATURE SERVICE

5.1 GAS TURBINES AND TURBOSUPERCHARGERS

Early in 1942, the Bureau of Ships, Navy Department, indicated an urgent need for better heat-resisting alloys than those then available for use in the construction of gas turbines for ship propulsion. It was stated that alloys were needed for use in fabrication of turbine buckets which would show a creep rate not in excess of 0.00001 per cent per hour at 1500 F and stresses of 7,000 psi.

The Office of the Coordinator of Research and Development, Navy Department, requested NDRC to institute a research program to evaluate the known alloys and to develop and test new and improved alloys for the desired service requirements. Project NRC-8 (N-102), Heat-Resisting Metals for Gas Turbine Parts, and Project NRC-41 (N-102), Heat Treatment of High-Temperature Alloys, were established to carry out this research program.

Long-time high-temperature tests require special equipment and special techniques possessed by only a few research laboratories which have specialized in this type of testing and have gained the experience required to produce reliable results. Several government laboratories and some dozen other laboratories, the latter heretofore occupied with the high-temperature problems of industry, possessed this experience and test equipment. The facilities of these laboratories were largely diverted from their previous activities to this heat-resisting alloy problem.[a]

Most of these laboratories put practically all of their facilities and personnel for high-temperature research on this work directed by the War Metallurgy Committee.

At the same time, research sponsored by the National Advisory Committee for Aeronautics and conducted at the University of Michigan was determining the tensile and stress-rupture properties at 1200 and 1350 F of many heat-resisting alloys in order to evaluate their usefulness for turbosupercharger and gas turbine wheels.

In the NRDC program, the temperature of interest was stated initially to be 1500 F, but the scope of the research was broadened to cover long-time creep testing at the lower temperature of 1350 F and all types of tests at 1600 F. Later tests were run on the better alloys at 2000 F.

In the NACA program, all types of tests were run at 1200 F, stress-rupture tests were made at 1350 F, and, more recently, some of the promising alloys were tested at 1700 and 1800 F.

The two concurrent research programs sponsored by NACA and NRDC were carefully coordinated to eliminate duplication of effort and to provide all types of test data over the entire temperature range from 1200 to 2000 F.

The requirements of the Bureau of Ships, Navy Department, for alloys for long-time service required final evaluation of the properties of the most promising alloys in long-time tests, or creep tests of at least 2,000 hours' duration. However, because of limited test equipment and manpower, it was necessary to compare the available alloys and to evaluate new alloys first by stress-rupture tests which determine the stresses required to produce rupture in given shorter time periods such as 10, 100, and 1,000 hours.

Activities of the Bureau of Aeronautics, Navy Department, developed the need for alloys suitable for use at higher stresses than 7,000 psi at 1500 F, but with shorter requirements for useful life. In the stress-rupture tests used for developments of alloys of the desired low creep rate, considerable data of direct value for this purpose were obtained. Only those alloys indicated as promising were subjected to long-time creep testing.

Tests were made on 96 heat-resisting alloys. These alloys were principally of Cr-Ni-Fe, Co-Cr, Cr-Ni-Co,

[a] Under OSRD contracts, laboratories of the following organizations were engaged to work cooperatively on the project: American Brake Shoe Company, Battelle Memorial Institute, Climax Molybdenum Company, Crane Company, Federal Shipbuilding and Drydock Company (United States Steel Corporation Research Laboratories), Lunkenheimer Company, The Massachusetts Institute of Technology, Midvale Company, National Bureau of Standards, University of Michigan, Vanadium Corporation of America, and Westinghouse Electric and Manufacturing Company.

Additional data and cooperation were supplied by the following organizations not under OSRD contract: Allegheny Ludlum Steel Corporation, Crucible Steel Company, General Electric Company, Haynes Stellite Company, International Nickel Company, Inc., Union Carbide and Carbon Company, Universal Cyclops Steel Corporation, and U. S. Naval Engineering Experiment Station.

and Cr-Ni-Co-Fe bases. Some were made available in wrought form while others were supplied in the form of precision-cast test pieces. Tests were also made on material cut from large forged disks of four heat-resisting alloys. Alloys for high-temperature service contain a considerable amount of chromium to confer resistance to oxidation, and a considerable amount of nickel or cobalt or both to render the alloy austenitic, since austenitic alloys far surpass ordinary ferritic steels in high-temperature strength. Rather generous additions of carbide-forming elements, such as molybdenum, tungsten, columbium, titanium, and tantalum, either singly or in combination, whose carbides can be separated out by a precipitation-hardening type of heat treatment, further raise the high-temperature strength. For each of these alloys it was necessary to work out the optimum heat treatment. The required time and temperature for solution of the carbides, the cooling rate from the solution temperature, and the reheating or aging time and temperature all had to be determined experimentally. Detailed heat treatment experiments were carried out on seven alloys under Project NRC-41, Heat Treatment of High Temperature Alloys.[188,191]

In addition to the stress-rupture and creep properties determined for the various alloys, impact resistance and short-time tensile properties were determined at selected elevated temperatures. For determination of stability of the alloys, hardness, impact resistance, and tensile strength were determined on material after long-time testing in stress-rupture or creep tests.

The numerous tables, figures, and graphs in the various progress reports show in detail the properties of all the alloys tested.[190-193] For the stress-rupture and creep tests, the actual time-deformation curves were presented to facilitate comparisons between the alloys by designing engineers on bases other than those arbitrarily chosen by the War Metallurgy Committee Research Supervisor for the program. The order of superiority of the alloys is not the same at different temperatures; moreover, at some temperatures forgings appear better than castings, while at others, the reverse is true. Extrapolations are dangerous, actual tests or evaluation of alloys under service operating conditions being desirable.

At the start of this work in early 1942, the War Metallurgy Committee conducted a survey of the current data on alloys suitable for high temperature service in gas turbine and supercharger parts. This survey, Project SP-5, was made in collaboration with the Naval Engineering Experiment Station and NACA.[194] It was found that only limited data were available on about six heat-resisting alloys indicative of promise for gas turbine and turbosupercharger service. Of these alloys, two showed a stress for 1,000-hour rupture and 1500 F at 9,000 and 11,000 psi, while two others were somewhat stronger and showed about 15,000 psi for rupture in 1,000 hours. Creep-test data were available at 1500 F for only one alloy and this gave a creep rate of 0.00001 per cent per hour at about 5,000 psi, whereas the Navy Department desired a material with this creep rate at 7,000 psi or higher.

At the termination of the NDRC work, nine cast alloys were known with 1,000-hour rupture at 1500 F in excess of 20,000 psi and up to 26,000 psi. Six forged alloys were known with 1,000-hour rupture at 1500 F between 15,000 and 18,500 psi.

At 1600 F, the cast cobalt-base alloys were definitely superior to the forged alloys with rupture in 1,000 hours between 14,500 and 17,500 psi as compared with 8,000 to 10,000 psi for the best forged alloys.

At 2000 F, the best cast cobalt-base alloys showed rupture in 100 hours between 4,000 and 5,000 psi.

In the creep tests, at 1500 F cast alloy X-40 showed the best creep resistance with a stress of 11,000 to 12,000 psi indicated for a creep rate of 0.00001 per cent per hour. All the other cobalt-base alloys, with the exception of Vitallium, are indicated to be above 8,000 psi for this rate of creep. Four of the forged alloys showed creep rates of 0.00001 per cent per hour at 7,000 psi or higher, with one alloy indicated between 10,000 and 11,000 psi.

Creep tests were made at 1350 F on those alloys showing promising properties at 1500 F. The better forged alloys, as a group, had better creep resistance at 1350 F than did the cast alloys, a relationship reversed from that at 1500 F.

Creep tests at 1600 F indicated that several of the forged and cast alloys met at this temperature the requirements which had been set as the original goal at 1500 F.

For four of the forged alloys which tests on bar stock indicated as promising for use as gas turbine rotors, large forged disks were obtained and high-temperature tests over the temperature range 1200 to 1500 F are in progress jointly between NACA and

the Navy Department on material cut from various locations in the disks.

It is certainly to be expected that among the possible combinations of precipitation-hardening elements in an austenitic matrix, new elements or combinations, some as yet untried, may be materially superior to those so far evaluated.

The Vanadium Corporation of America, one of the contracting laboratories on Project NRC-8, melted and cast a large number of Cr-Ni-Co and Cr-Ni-Co-Fe base alloys with considerably higher molybdenum or tungsten additions than the majority of the alloys tested in the balance of the program. Preliminary appraisals of the effects of these additions were made by means of high-temperature hardness determinations. In these alloys, the effects of additions of other elements, including vanadium, boron, beryllium, titanium, and aluminum on the hot hardness were also determined. Some of these alloys possess very high hardness at 1500 F, some as high as 400 Brinell. Stress-rupture properties at 1600 F have been determined on a few of these alloys. Ductilities upon rupture tend to be low. Testing was restricted by lack of facilities, but at least four of the alloys show properties at 1600 F superior to those of the best cast cobalt-base alloy. It is obvious that there is opportunity for still further improvement in this family of alloys, improvements that might be of great portent to the gas turbine. To date, the effects of carbon content, heat treatment, and melting practice (deoxidation and grain size) on strength and ductility are not known.[195]

However, attention has not been confined in the heat-resisting alloy program to the families of alloys previously discussed. Other families, whose processing and fabrication offer such difficulties that past investigators have done little or no serious work on them and whose properties were entirely uncharted, might be so much better that the difficult job of working out their fabrication problems might be well worth tackling. The value of super high-temperature alloys in gas turbine service is so great that cost of raw material and processing, which would be prohibitive for less important uses, is no barrier.

With these aspects in mind, the Climax Molybdenum Company, one of the contracting laboratories on Project NRC-8, surveyed the field of possible new alloy systems. Various binary and ternary alloy systems formed using elements with melting points considerably in excess of the presently used alloys were investigated, including chromium, molybdenum, tungsten, columbium, platinum, thorium, vanadium, and zirconium. Considering availability and properties, the most interesting of these refractory metals is chromium. An outstanding presentation of the properties of the alloys of chromium and the methods of melting, purifying and shaping of the alloys has been made by the Climax Molybdenum Company in two reports.[196,197]

The alloys having the best combination of strength and ductility at 1600 F were found in the composition range from 60% Cr, 35% Fe, 5% Mo to 60% Cr, 15% Fe, 25% Mo. Alloys with 60% Cr and between 15 and 25% Mo, balance iron, show rupture times at 1600 F and 30,000 psi as long as those of the best cobalt-base alloys at 20,000 psi. Heat-treatment experiments indicate still greater promise for these alloys, and the study of these chromium-base alloys containing iron and molybdenum is being continued at Battelle Memorial Institute under the sponsorship of the Office of Research and Invention, Navy Department.

Service tests under actual gas turbine operating conditions have been arranged for most of the promising bucket alloys whose properties were determined. Some are under test at the U. S. Naval Engineering Experiment Station in a General Electric turbosupercharger using hot gas produced from combustion of Navy Bunker C fuel oil. Other alloys, including alloys from the Vanadium Corporation and the Climax Molybdenum Company work, have been installed and are being tested in a Westinghouse aircraft gas-turbine jet-propulsion engine. These service tests are still in progress, so comparisons between the alloys which possess somewhat different strengths and ductilities are not yet available.

In some types of high-temperature service, notably those with rotating parts, there is likelihood of vibration which may set up extraordinary stresses so that the behavior of the alloys in fatigue and notch fatigue at operating temperatures should be known. From this point of view, the ability of the material itself to damp out vibrations at operating temperature is also of interest. The Westinghouse Electric and Manufacturing Company has made available a large quantity of fatigue data determined in their own laboratory and these data have been reported in the progress reports on Project NRC-8. Some high-temperature fatigue work was begun and will be continued under a Navy Department contract. As

would be expected, alloys which show outstanding resistance to deformation under stress at high temperatures, also tend to have low damping capacity, and vibration apparently must be avoided by means other than by choice of material. Data on the damping capacity of some of the high-temperature alloys were collected and compiled.[198] (See also Section 5.3 of this report.)

Assembly of buckets on gas turbine rotors is facilitated if welding can be used. In June 1944 the War Metallurgy Committee Project Committee for the heat-resisting alloy program reported that a number of turbine fabricators were experiencing welding problems and that there was a serious need for weldability data on the newly developed heat-resisting alloys. Three types of weld joint defects were reported to occur in welded wheels as follows: (1) notch extensions or a form of cracking which initiates at the junctions between buckets on the outer edge of the weld metal and propagates radially across the welded joint eventually reaching proportions endangering the strength of the wheel; (2) weld metal bead cracking in the form of longitudinal cracking in the center of the deposited weld bead and also in the form of scattered intergranular fissures; and (3) under bead cracking in the fusion zone and heat-affected zone in heavier section buckets of jet unit and gas turbine wheels. In order to investigate these problems and to evaluate the relative weldability of a series of selected alloys, Project NRC-90 (N-102), Weldability of Heat-Resisting Alloys, was established in the laboratories of the Rustless Iron and Steel Corporation in July 1944.

Simple weld tests were investigated in an attempt to produce the defects encountered in welding heat-resisting alloys by the submerged-melt and manual-arc processes. A wheel-and-bucket design test was ultimately developed and, of 80 such tests planned, about one-third had been completed by October 1945 when the NDRC project was terminated.[199] Sufficient work completed to show that wide variations exist in the susceptibility of different heat-resisting alloys to the development of welding defects. This welding work is being continued by the Rustless Iron and Steel Corporation under a Navy Department contract with Battelle Memorial Institute.

The results obtained in the heat-resisting alloy program have indicated that improvements made in the alloys now commercially available exceed the requirements originally set by the Navy Department, and still further improvements are to be expected, particularly in the new alloy systems investigated. The data of the program were presented in comprehensive reports,[188-191,193,200,201] An index[201a] of the Division 18 reports on heat-resistant alloys was prepared by the Research Information Division of the War Metallurgy Committee. This index gives a subject index of the various reports issued on each, a numerical list of reports with a brief abstract of the contents of each, and a subject-index of the reports. It lists also the alloys investigated. Several special reports not specifically mentioned in the foregoing discussion also were issued as follows: *Survey of Data on Alloys Developed for Turbosupercharger and Gas Turbine Applications,*[192] *Machining Data on Heat-Resisting Alloys,*[201] *Metallurgical Investigation of a Large Forged Disc of Low-Carbon N-155 Alloy.*[202] The last-named joint NDRC-NACA report brought together the data of the NDRC and NACA projects on the subject. At the specific request of the Armed Services, these reports were distributed to their contractors who were concerned with the development and use of heat-resisting alloys. The data presented have had wide use by designing engineers in specifying designs and materials for improved gas turbine power plants for marine and aircraft use now under construction.

Research on heat-resisting alloys of the more common Cr-Ni-Fe and Cr-Ni-Co-Fe types was carried out by the American Brake Shoe Company under Correlation Project NRC-84A, Heat Resistant Alloys for Ordnance Matériel and Aircraft and Naval Engine Parts. This program, which was financed by the American Brake Shoe Company and conducted under the general supervision of the War Metallurgy Committee, covered comprehensive studies of alloys of the 21% Cr, 9% Ni type as substitutes in applications below 1600 F for the widely used 26% Cr, 12% Ni type.[203] The effects of cobalt and nickel in two groups of 26% Cr alloys, one group essentially non-ferrous and the other containing 50 per cent of iron also were investigated.[204]

The cooperation of the alloy producers, the gas turbine contractors, and the contracting research laboratories in the prosecution of the work under the NDRC heat-resisting alloy program was outstanding and is a shining example of the willingness and ability of industry to cooperate in solving mutual problems.

5.2 ROCKETS AND JET PROPULSION DEVICES

The Special OSRD Committee on Jet Propulsion, in its report dated March 20, 1944, recommended that those engaged in the development of rocket motors for solid fuels obtain the aid and advice of Division 1, NDRC, and the War Metallurgy Committee (Division 18, NDRC) on materials for nozzle construction.

Project NRC-88 (AC-75), Metal and Ceramic Materials for Jet Propulsion Devices, was established at Battelle Memorial Institute to provide advice and assistance to the Armed Services, their contractors, and other NDRC divisions engaged in the development of jet propulsion devices in matters concerning materials of construction for both solid-fuel and liquid-fuel rocket motors.

For this work, in addition to the facilities of Battelle Memorial Institute, cooperation and assistance was obtained from Division 1, NDRC, from metal and alloy producers, and from commercial producers of ceramic shapes. Assistance on material problems was supplied to Allegheny Ballistics Laboratory, Division 3, NDRC; Explosives Research Laboratory, Division 8, NDRC; California Institute of Technology; Bureau of Aeronautics, Navy Department; and the Aerojet Engineering Corporation.

Because of the successful application of chromium plate in machine gun liners by Division 1, NDRC, similar chromium plates were tried as protective and erosion-resistant coatings in rocket nozzles. In nozzles of liquid-fuel units burning mixed acid and aniline, chromium-plated coatings gave very satisfactory service. In one trial, a copper nozzle plated with 0.009 in. of soft low-contraction chromium was subjected to 14 firings totaling 79½ minutes and was still in a satisfactory condition. The use of chromium-plated nozzles in solid-fuel units was not so successful. Blistering and cracking of the plated coatings occurred, even though suitable adhesion of the plate was obtained in most cases.

Many firing trials were made in solid-fuel units on nozzles coated with tantalum, molybdenum, and tungsten by vapor phase methods by Battelle Memorial Institute and by Bell Telephone Laboratories, a contractor of Division 1, NDRC. While it was indicated that these metals possess usable corrosion and erosion resistance, satisfactorily consistent ductility and adhesion of the coatings to the metal comprising the nozzle were not obtained.

Firing trials on nozzle inserts of pure chromium and high-chromium Cr-Mo-Fe alloys, prepared by the Climax Molybdenum Company, showed these materials to be of considerable promise in that erosion was practically nil. Further trials of these materials seem warranted and desirable.

Ceramic nozzles of alumina, zirconium silicate, and beryllia were prepared by Battelle Memorial Institute, and ceramic nozzles of commercial and pure refractories of the alumina and silicon carbide types were prepared by the Norton Company and the Carborundum Company. Several additional commercial ceramic nozzles were supplied by the General Electric Company. In firing tests, all of these ceramic nozzles were cracked, probably as a result of lack of the necessary heat-shock resistance. None of the ceramic nozzles, except for beryllia, were found to be erosion resistant, and considerable roughening of the surface and spalling was observed.

Tungsten carbide and boron carbide nozzle inserts were tested. Both of these materials, on limited trials, appear to show satisfactory erosion resistance, but nozzles of both materials were cracked. This cracking may be the result of stresses set up by heating and cooling of the steel holders in which the nozzle inserts were mounted, rather than lack of heat-shock resistance. These materials, particularly the boron carbide, deserve further study for applications requiring nozzles of exceptional performance. It should be noted that fabrication of the ceramic or carbide nozzles in a number of pieces divided along the nozzle longitudinal axis might relieve the stresses set up sufficiently to prevent additional cracking. The Aerojet Engineering Corporation was supplied ceramic nozzles for test by the Norton Company, but no report of their performance has been received.

Assistance on material problems to the Bureau of Aeronautics, Navy Department, included chromium plating of a stainless-steel nozzle, and chromium plating of a pump shaft, both used in an acid-aniline motor. The chromium-plated nozzle sustained no damage in nineteen runs totaling 23 minutes using jet velocities up to 6,900 fps with chamber pressures between 300 and 550 psi absolute. Considerable work was under way for the Bureau of Aeronautics to find materials suitable for bearings, sealing rings, adhesives, and other component parts for the acid pump used in this motor, but the work was incomplete when the project was terminated in accordance with

the demobilization schedule of NDRC.

Failures of reed springs operating in the temperature range 900 to 1000 F used in buzz bombs led to a request for assistance by the Aerojet Engineering Corporation. The failures were apparently fatigue failures. Data presented in the final report on the heat-resisting alloy program[193] indicate which materials have outstanding elevated-temperature fatigue resistance. Strip 0.010-in. thick of three of the most promising alloys (Battelle 8-J, Hastelloy B, and Inconel X) was fabricated into reed springs and heat treated to produce maximum spring and fatigue properties for service at 900 to 1000 F. These reed springs were submitted to the Aerojet Engineering Corporation for trial, but reports on their performance are not as yet available.

Some of the materials tried in the various firings and service applications noted above were sufficiently promising to warrant further trials and consideration in rocket development work.[205] Multipiece ceramic nozzles, boron carbide nozzles, and nozzles of melted and cast pure chromium and chromium-base alloys deserve further study for these applications.

5.3 RESEARCH NEEDS IN THE FIELD OF HEAT-RESISTING ALLOYS

The NACA Committee on Materials Research Coordination compiled an index of the research projects on heat-resisting alloys carried on during World War II. During the committee's discussions of the adequacy of the research programs carried out by the Armed Forces, NACA, and NDRC, the need for a compilation of the properties of sheet materials for high-temperature service and a bibliography on the damping of metals was emphasized. At the committee's request, the War Metallurgy Committee established and carried out two surveys: Survey Project SP-31, Properties of Sheet Materials for High-Temperature Service, and Survey Project SP-33, Bibliography on the Damping of Metals. The report on SP-31[206] covers the properties of materials used in fabricating jet engine combustion chambers, ducts, exhaust collector rings, etc., while that on SP-33[207] covers test methods as well as data on the damping of metals.

Chapter 6

WELDING

6.1 ARMOR AND ORDNANCE WELDING

6.1.1 Introduction

Early in World War II the decision was reached to make use of welding as a principal method of fabricating much of the vast quantity of material needed in the armament program. Attention was immediately drawn to the problems involved in welding metals, which in many cases possessed different characteristics from those in common use before the war. Difficulties encountered by fabricators, particularly in the field of armor and alloy steel welding, soon made it apparent that a coordinated research effort to provide urgently needed information was essential to the maintenance of planned production.

At the suggestion of the Office of the Chief of Ordnance, several NDRC projects were established with the expectation that the resulting information would be of immediate value. Among the most urgent early problems requiring attention were an evaluation of the relative weldability of rolled homogeneous armor, the development of an armor welding electrode which when deposited would exhibit ballistic properties equivalent to rolled homogeneous armor, a study of procedures for welding face-hardened plate, and the development of a satisfactory substitute electrode containing the lowest practical amount of strategic alloy elements to replace the 25% Cr, 20% Ni type commonly used for alloy steels prior to the war. Less urgent problems included a study of the fundamental factors affecting the weldability of steels, the development of spot welding techniques for light armor, a study of methods for stress-relieving ordnance steels with special regard to machining stability and an investigation of the flash welding of aircraft steels. Associated studies were initiated as warranted, and other urgent problems, such as the repair welding of cast armor, were investigated as the war progressed.

Surveys both of literature and of industrial practice were conducted in the fields of armor welding and aluminum alloy flash welding preliminary to the establishment of research programs on various aspects of these subjects.

Throughout the war considerable aid was furnished by members of the staff of the War Metallurgy Committee to the fabricators of ordnance equipment in the form of field service and consultation on special problems that developed in the production of certain combat equipment.

6.1.2 Armor and Alloy Steel Welding

In order to determine the research needs in the field of armor and alloy steel welding, in July 1941 the Metallurgy Section of the former Division B of NDRC established a project to survey the literature and industrial practice. This survey was conducted by Ohio State University under Project B-150, Research Needs in the Field of Welding and Summary of Existing Knowledge on Welding Practice, and resulted in five comprehensive reports covering the research needs,[208] the then current industrial practices and procedures for the welding of armor,[209] available data on precipitation-hardening alloys used in armor welding (OD-36-2, OD-36-3),[210] data on the dilation characteristics of alloy steels used in ordnance (OD-37-1, OD-37-2) and their significance in welding,[211] and the evaluation and relief of residual stresses in welded ordnance structures (OD-34-2, OD-34-1).[212]

This survey disclosed that little information was available in this field and that industrial knowledge had not progressed to the point where standardized procedures were common from one plant to another. Each fabricator had experienced difficulties which were considered only in the light of the information and facilities available, and no unified effort had been directed toward the solution of the many basic problems involved.

Since armor plate compositions are not greatly different from certain classes of alloy steel in common use, the problem of weldability was not entirely new and considerable use of past information and methods of attack was employed in its solution. The problem of welding armor plate involves two broad aspects. These are, first, the production of sound, crack-free welds usually under conditions in-

volving high restraint, and, second, the subsequent performance of the weldment in service. Since the service requirements for welded armor plate obviously include ability to withstand ballistic impact, it was necessary to establish an arbitrary test early in the war in the hope that satisfactory performance under this test would insure satisfactory service.

The procedure finally adopted for evaluating the quality of welded armor involved the assembling of four pieces of armor in such a manner that the welded joints form the letter "H" on the completed plate. The test consists of subjecting alternate leg welds of the H plate to the impact of special projectiles which are primarily designed to evaluate the shock properties of the weldment. Details of the H plate test for various thicknesses of welded armor are to be found in Army Ordnance specifications on this subject.

Since the inability of either the armor or weld to withstand shock in extreme cases may result in complete disintegration of a combat vehicle, it was apparent that equipment subjected to ballistic attack with overmatching projectiles must be designed primarily to resist shock loading, with penetration resistance of secondary importance. Therefore, early production of armor weldments was accomplished with the use of austenitic electrodes which exhibited reasonably satisfactory shock-resisting properties with a fair degree of consistency. It also appeared that the use of austenitic electrodes in production could be satisfactorily controlled. As a result, most fabricators evolved successful procedures for welding armor using austenitic electrodes, first of the 25% Cr, 20% Ni type, and later as the result of alloy conservation, of the modified 20% Cr, 10% Ni type.

It was felt that research effort in the field of evaluating the weldability of commercial armor should be devoted to a study of methods of obtaining weldments with better shock properties than were being produced, and also, because of the disadvantages associated with austenitic welding and the need for conserving strategic alloying materials, to place increased emphasis on the development and use of ferritic electrodes. In addition, there was an urgent demand for an investigation to determine the causes of first pass cracking in austenitic 20% Cr, 10% Ni electrodes.

Accordingly three research projects were initiated and established in the spring of 1942: Project NRC-1 (OD-82), Weldability of Commercial Armor Plate, at the United States Steel Corporation Research Laboratories; Project NRC-2 (OD-36-2), Development of Ferritic Armor Welding Electrodes, at the Combustion Engineering Company; and NRC-2R, Development of Armor Welding Electrodes, at the Rustless Iron and Steel Corporation.

Development of Armor Welding Methods and Ferritic Armor Welding Electrodes

The primary objective of Project NRC-1, Weldability of Commercial Armor Plate, was not to find a method for welding armor, but rather to develop better methods than were in current use and to determine the causes of the erratic shock performance of identical weldments. Initial work included the preparation and subsequent ballistic testing of H plates fabricated using ferritic electrodes and different welding procedures. It should be noted that the assembly of an H plate involves the deposition of weld metal under high restraint, which enables an evaluation to be made of the combined effect of procedure, armor composition, and electrode on the ability to produce sound, crack-free joints, and provides direct information on shock performance when tested ballistically. Other primary functions of this project were the post-ballistic examination of weldments, such as H plates, to determine the fundamental causes for failure and to develop and investigate the suitability of laboratory tests for the prediction of ballistic properties. A detailed statement of the objectives of the project, together with an outline of the proposed H plate program and preliminary test results, is contained in an early progress report.[213]

Coincidental with the establishment of Project NRC-1 on the evaluation of the weldability of commercial armor, work was initiated on the ferritic electrode development phase of the armor plate weldability problem under Project NRC-2. The ferritic electrode development program was doubly important at the time because of the need for conservation of strategic alloys, such as nickel, chromium, and molybdenum, and because of disadvantages associated with the use of austenitic electrodes. Besides the first pass cracking difficulty mentioned previously, these disadvantages include shock properties inferior to prime armor, slow deposition rates which tend to decrease rates of production, the great difficulty of removing austenitic deposits during repairing, and the necessity for employing wide joints

to avoid failures resulting from localized deformation and rupture in the low-yield weld metal during ballistic attack, a factor which also tends to slow production.

Originally, it had been intended to treat this particular aspect of the armor welding program more or less separately, but overlapping with the more direct weldability studies was unavoidable, since the investigation of electrodes could not be accomplished without simultaneously considering all the variables inherent in the welding of armor. Early work on both projects was therefore closely integrated. The progress reports[213-216] complement one another, and the final reports[217-218] summarize briefly the work done and the results obtained.

In the course of the investigations referred to above, a considerable number of tests were conducted on H plate fabricated with ferritic electrodes. The majority of these early plates failed by a wide margin to pass the arbitrary shock requirements established for austenitic weldments. Analysis of the results of these tests tentatively attributed failures to several factors, the most important of which were as follows:

1. High residual stresses in and near the welds.
2. Microcracks not detectable by radiographic examination.
3. Excessively high yield strength of the weld metal.

Subsequent research, however, demonstrated the fallacy of these early conclusions.

With this information available, additional studies involving the influence of thermal stress relief on the performance of welded armor were initiated. An investigation of the residual stress pattern in a typical H plate was made which showed that high residual stresses approaching the yield strength of the weld metal are present in completed H plates.[219] To determine the effect of thermal stress relief treatments on the hardness of commercial rolled homogeneous armor, a study was made which demonstrated that the hardness of five types of rolled armor is reduced for treatment temperatures above 1100 F.[220] Since reductions in hardness lower the ballistic penetration resistance and may adversely affect toughness, thermal stress relief treatments cannot be considered desirable. Practical difficulties encountered in stress relieving large armor weldments are of course obvious.

Extensive studies to determine the magnitude and distribution of residual stresses in the longitudinal, transverse, and thickness direction in welded plates were made at the Massachusetts Institute of Technology under Project NRC-53 (OD-106), Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor. An analysis of the effect of residual stresses on ballistic shock performance, as measured by a direct explosion test, indicated that the residual stress pattern has but minor influence on the shock resistance of weldments and that the major cause of failure involves purely metallurgical factors.[221-223] Subsequent tests of H plates confirmed these conclusions.

Further investigation of commercial and experimental ferritic electrodes under Project NRC-2 at the Combustion Engineering Company, using bead-crack sensitivity and restrained joint tests, established the fact that these tests afforded practical methods for comparing electrode cracking tendencies. With these tests and the cooperation of the arc welding electrode industry, a large number of commercially available ferritic electrodes were screened to determine their suitability for armor welding applications. The results of this early study provided sufficient data to eliminate all low-tensile ferritic electrodes from further consideration and to concentrate attention on a few high-tensile electrodes[215]

After the first few restrained joint tests, the results obtained with a Mn-Mo-Si electrode with a lime-type coating were so favorable in comparison with the other high-tensile ferritic electrodes that all efforts were turned toward improving and investigating this type of electrode termed the NRC-2A electrode. It had been noted during the bead-crack sensitivity work that cracking consistently occurred in the heat-affected base metal of current armor compositions whenever ferritic electrodes of the conventional type were used without preheat. The extent of cracking varied with both the electrode and the type of armor, and high preheat was known to eliminate this underbead cracking tendency. It was also noted[215] that underbead cracking did not occur in the base metal when austenitic electrodes of either the 20% Cr, 10% Ni, or the 25% Cr, 20% Ni type were used and that the Mn-Mo type of electrode coated with a mineral-type coating similar to that used on all austenitic electrodes did not produce cracking. The reasons for this difference in the cracking tendency for single or multibead deposits were not completely clear during the early stages of the investigation. The

most important reasons advanced for the noncracking characteristics of the special Mn-Mo electrode were:

1. A difference in the composition of the arc atmosphere produced by the lime-type coating. It was felt that this difference would result in lower gas content, particularly hydrogen, and reduced embrittlement in the heat-affected zone. It is significant to note that this was the first time it was felt that the heat-affected zone cracking was associated with hydrogen in the arc atmosphere.

2. A smaller amount of expansion during transformation resulting in lower stresses in the weld region.

As soon as the difference in the properties of the Mn-Mo electrode became apparent, experimental H plates were prepared and ballistically tested. From ballistic results obtained for the first plates tested, the following tentative conclusions were drawn:

1. Most of the plates passed the shock test requirements established for austenitic weldments.

2. None of the plates failed as badly as did the majority of H plates welded with other types of ferritic electrodes.

3. A few of the H plates tested performed better than any H plate previously tested and closely approximated the shock performance of unwelded rolled homogeneous armor.

4. The effect on shock resistance of heat treatment following welding did not appear beneficial.

As a result of these observations, the ferritic electrode development phase of the armor weldability problem was modified and directed towards a thorough investigation of the Mn-Mo type electrode. It was felt that to develop further the information already available, pertinent studies should include the following:

1. The development of an optimum composition of the NRC-2A electrode (Mn-Mo type) for ballistic application.

2. The development of a modified lime-type coating possessing better operating characteristics than that used on the original electrodes.

3. A fundamental investigation of the factors involved in improving electrode coatings. This study also planned an investigation of the arc atmospheres produced by various types of electrodes.

Accordingly, a fundamental investigation of electrode coatings was established in January 1944 at Battelle Memorial Institute under Project NRC-76 (OD-36-2), Development of Improved Electrode Coatings. Initial work on the project was entirely devoted to a study of the gases present in arc atmospheres and their effect on underbead cracking, since this subject was of particular interest in explaining the noncracking characteristics of the Mn-Mo ferritic electrode. The investigation showed that the lime-coated ferritic and austenitic armor welding electrodes which do not cause underbead cracking produced arc atmospheres low in hydrogen with appreciable amounts of carbon dioxide. Conventional ferritic electrodes of the mild and alloy steel types with cellulosic and related coatings consistently produced underbead cracking and are characterized by arc atmospheres high in hydrogen.[224] A continuation of experimental work to obtain more data pertaining to underbead cracking in hardenable alloy steels led to a study of commercial and experimental coated electrodes. Additional tests were made using synthesized arc atmospheres to determine the effect of individual gases on underbead cracking and also to determine the effect of the arc upon these gases.[225,226] These tests definitely prove that hydrogen is directly responsible for underbead cracking in hardenable steels. Other investigations show that this cracking tendency is also affected by metallurgical factors.

At the request of Watertown Arsenal, later work on this program was devoted to determining the causes of weld metal porosity during metal arc welding. Variations in porosity were found to be associated with the presence of hydrogen, nitrogen, and water vapor.[226] It appears desirable to point out that these investigations were terminated in August 1945 before the work had progressed to a logical conclusion. The continuation of these studies should provide much useful information which ultimately should be of considerable value in minimizing arc welding problems.

While the above investigations were in progress, work was also continuing on the armor plate weldability problem and ferritic electrode development program. Both investigations were closely integrated and were concerned with the further improvement and application of the NRC-2A electrode (Mn-Mo) to the welding of armor. A large number of H plates were fabricated by various procedures using commercial versions of the NRC-2A electrode, which by this time was being produced in appreciable quantities. The results of ballistically testing these H

plates are summarized in two reports[216,227] which conclude that the use of ferritic welding under controlled conditions will insure weldments possessing shock properties equal to or superior to corresponding austenitic weldments. Improvements were made in the operating characteristics of the Mn-Mo electrode and subsequent ballistic tests of weldments, such as an M-5 tank hull, showed that it is possible to fabricate successfully large armor weldments with this electrode.[227] As a result of these observations, a suggested specification for the NRC-2A electrode was prepared[228] which was subsequently adopted as Ordnance Department tentative Specification AXS-1450.

Attempts to improve the operating characteristics of the NRC-2A electrode were continued under Project NRC-2. The effects of changes in the constituents of the electrode coating were investigated to determine the effect of such changes on operating characteristics, porosity, and weld metal properties.[218] This information remains incomplete because it was considered necessary to drop this phase of the investigation in order to take up the more urgent problem of the development of electrodes for the repair welding of heavy cast armor. This work is discussed later in this chapter.

A fundamental investigation of the isothermal transformation characteristics of NRC-2A weld metal was made under Project NRC-1, which indicated that the deposited metal from this electrode should consist of acicular ferrite and tempered martensite. This structure was attributed to the rapid and extensive formation of acicular ferrite in the vicinity of 1000 F during cooling which results in carbon enrichment of the residual untransformed austenite. With the cooling rates associated with arc welding, no transformation occurs at intermediate temperatures and, as a consequence, martensite rather than a ferrite-carbide aggregate is formed.[229,230]

Another study pertaining to the properties of NRC-2A electrode was conducted at the International Harvester Company, Inc., and showed that a pronounced aging effect, resulting in improved ductility, is obtained when NRC-2A deposits are tested after various elapsed times at room temperature. Ductility is also shown to increase further as the result of treating the weld metal for various times at low temperatures. This effect is believed to be associated with elimination of hydrogen from the deposit.[231]

Work was also undertaken involving the post-ballistic examination of ferritically welded ½-in. H plates to determine the fundamental causes of poor shock properties. This work shows that ballistic performance is affected by several factors including weld metal structure and properties, armor composition, joint design, and welding procedure, and that failure usually occurs in shock-deficient metallurgical structures adjacent to welds.[232] Other experiments to compare different types of commercial NRC-2A electrodes exhibiting good and bad shock properties also were carried out.

Study of Causes and Manner of Failure of Welded Joints Under Ballistic Shock

An extensive study was made under Project NRC-1 at the United States Steel Corporation Research Laboratory to determine the causes and manner of failure of welded armor joints subjected to ballistic impact. A large number of weldments primarily H plates but including actual components of armored vehicles, were examined, and the path of fracture in these weldments was determined and correlated with the zone of the joint through which the fracture traveled. In addition to establishing the mechanism for failure under ballistic shock, procedures for improving the shock resistance of welded joints were recommended.[217,233-236] The most important facts and conclusions revealed by these studies were:

1. Ballistic fractures propagate through the weld, the bond zone, or the heat-affected zone, whichever has the least ability to absorb energy under shock loading.
2. In weldments made with high rates of heat input for the cross section available, the unusually low rate of cooling produces a zone of weakness in the heat-affected portion of the parent metal next to the weld with the armor compositions used for most combat vehicles.
3. Submerged-melt, automatic, and manual welding of thin sections up to ½ in. in thickness usually results in cooling rates sufficiently low to permit the formation of a zone of weakness in the heat-affected zone of commercial armor compositions used for most combat vehicles. Ballistic failures usually occur in this region.
4. Ballistic failures of weldments made with austenitic electrodes usually occur in the weld metal adjacent and parallel to the interface between the weld metal and the heat-affected zone, provided no

weakness exists in the latter region. This type of fracture is believed to be caused by a linear precipitation of carbides and nonmetallics in the weld metal immediately adjacent to the interface.

5. Excessive dilution of austenitic weld metal with parent metal (particularly in narrow joints) makes the weld deposit less shock resistant. Failure has been found to occur consistently if the iron content of the weld deposit is greater than 70 per cent.

6. Weldments made using ferritic electrodes exhibit shock properties superior to corresponding austenitic weldments and in many cases develop shock resistance approaching that of unwelded armor. These ferritic welds were made in an arc atmosphere low in hydrogen and the deposits are characterized by a microstructure consisting of acicular ferrite and tempered martensite which has been found to be associated with superior shock resistance.

7. Conventional tensile properties, such as yield strength, ultimate strength, and ductility, as determined by standard tests, do not correlate with the ballistic shock resistance of any part of the welded joint.

Direct Explosion Test for Welded Armor

Since it was necessary to evaluate the ballistic shock performance of welded armor in order to insure satisfactory service performance, it was felt that a simpler test for this purpose would be extremely valuable. As a result, an investigation involving the determination of shock properties by static detonation of explosive charges, either in contact with or closely adjacent to prime and welded armor, was undertaken at the Trojan Powder Company under Project NRC-25 (OD-76) (NS-255), Direct Explosion Test for Welded Armor and Ship Plate. Activity on this project resulted in the development of testing procedures and special explosives which, when detonated in direct contact with either welded or prime armor, enables the relative shock performance of the steel or weldment under investigation to be ascertained. It is possible with this type of test to differentiate between the quality of different heats and types of armor, alloy, and mild steel, and to evaluate the effect of welding with different procedures. The results obtained with the explosion tests closely approximate the results obtained for standard ballistic tests made with projectiles. However, it should be noted that, although the explosion test does not exactly duplicate the ballistic test, it does provide a shock test of sufficient severity to accomplish the same objective.[81,82,237] This project is also discussed in Section 2.2 of this report in connection with nonballistic testing methods. Although work has terminated in connection with the application of this test to armor and ordnance equipment, other development work in applying the explosion test to evaluate the performance of ship plate and high-tensile hull steel is being conducted for the Navy Department under a direct contract with the Bureau of Ships.

Development of Austenitic Electrodes

While the above investigations were being conducted, work on the development of noncracking austenitic armor welding electrodes was progressing at the Rustless Iron and Steel Corporation under Project NRC-2R, which was financed by the company and conducted under the supervision of the War Metallurgy Committee. The objective of this investigation was to determine the cause of root pass cracking and to investigate the relative advantages of manganese versus molybdenum modifications of 20% Cr, 10% Ni electrodes. Details are described in three reports which comprehensively cover the work done.[238,239,240] The important conclusions drawn indicated that it is possible to eliminate weld metal cracking in austenitic deposits of the modified 20% Cr, 10% Ni type by properly balancing the carbon, nickel, chromium, manganese, and molybdenum contents. Modifying the composition of the weld deposit so that a small amount of delta ferrite is developed minimizes the tendency for cracking. There appears to be an optimum amount of this phase which will give best results. Satisfactory electrodes can be made using either manganese, molybdenum, or combinations of these metals, provided proper alloy balance is maintained. A composition balancing factor was developed which relates the carbon and alloy content of the weld to its structure.

Significantly, it was disclosed that although both the mechanical properties and the cracking tendency of austenitic electrodes are affected by changes in composition, no relation exists between the ballistic properties of austenitic weldments and the composition of the deposited electrode. The ballistic performance of several types of rolled homogeneous armor welded with austenitic electrodes, as evaluated by a direct explosion test, revealed variations which were ascribed to the armor used in the tests.

Application of Large Diameter Electrodes

A survey was made by the War Metallurgy Committee on the application of large diameter austenitic electrodes to the welding of armor.[241] It was concluded that, while the use of large-size electrodes (3/8 in. and 1/2 in.) would materially increase rates of production, in armor applications their use should be limited to sections not less than 1 1/2 in. thick, since ballistic tests indicated that the high heat input associated with large diameter electrodes produced shock-deficient metallurgical structures in plates up to 1 in. thick.

Low-Temperature Ballistic Performance of Welded Armor Plate

As a result of the poor ballistic shock performance exhibited by prime and welded armor at subnormal temperatures, the Army Ordnance Department's Tank Automotive Center in Detroit requested an investigation of the causes for failure of welded plates tested during the Canadian Cold Test Program of 1942-1943. This study was conducted also by the United States Steel Corporation Research Laboratories under Project NRC-1 and included H plates welded by the automatic Unionmelt process, H plates manually welded using 20% Cr, 10% Ni, 4% Mn electrodes, and H plates manually welded with 20% Cr, 10% Ni, 2% Mo electrodes. Because of the urgency of the work, these problems were assigned to research laboratories of the United States Steel Corporation, the International Nickel Company, and the Climax Molybdenum Company, respectively, with overall coordination provided by the United States Steel Corporation investigators.

The investigation of the automatic process disclosed that the path of fracture in the ballistically tested H plates was predominantly in the heat-affected zone of the armor adjacent to the weld. The primary cause of failure in this region is believed to be due to the combined effect of unfavorable armor composition and to the high rate of heat input characteristic of the submerged-melt process, both of which result in the formation of free ferrite and other high-temperature shock-deficient transformation products. Other contributing factors, which appear to be magnified at subnormal temperatures, are the presence of local stress concentrations resulting from excessive weld reinforcement and defective welding. Recommendations for improving both austenitic and ferritic Unionmelt welded armor are also presented in the report of this work.[233]

The investigation of H plates manually welded with Cr-Ni-Mn austenitic electrodes attributed failure at low temperatures to excessive weld metal hardness in the root passes resulting from a low austenitic margin.[234] Studies of H plate failures manually welded using Cr-Ni-Mo austenitic electrodes showed that the fracture path obtained in the low-temperature tests occurs at the interface between the weld and base metals and appears to alternate between these regions.[235] This type of failure was attributed to shearing stresses developed at the weld interface as a result of cooling the armor and the austenitic weld metal which possesses greatly different coefficients of expansion at low temperatures. Other investigations have shown a linear precipitation of carbides and nonmetallics in the weld metal very close to the base metal interface, a factor which undoubtedly plays an important part in failure at this location.

Development of Welded Backup Strips

Research involving the development of backup materials for welded armor joints was established in May 1943 at Battelle Memorial Institute under Project NRC-59 (OD-82), Non-Metallic Welding Back-Up Strips for Armor Plate Joints. This program was particularly concerned with nonmetallic materials because of difficulties attendant to removing steel bars and because of the fact that copper tends to melt, diffuse, and thereby alter the composition of the first weld pass. This sometimes causes porosity and cracking in certain weld metal compositions. Mineral-coated metallic strips and tamped granular ceramic materials were developed and applied with considerable success to austenitic and ferritic weldments in armor, alloy, and mild steels.[242,243,244]

Effect of Oxygen Cutting on Weldability

Another project, directly related to the armor weldability investigation, was initiated as the result of a request made by the Army Ordnance Department's Tank Automotive Center in Detroit. This project, Project NRC-71 (OD-136), Effect of Oxygen Cutting on Weldability of Armor Plate, was established in October 1943 at the Air Reduction Company, Inc., to study cracking associated with oxygen cutting, grooving, and gouging operations on rolled and cast homogeneous armor. Originally it had been

contended that cracks resulting from flame cutting operations made preparatory to welding were partially responsible for poor ballistic properties. Therefore, one of the primary purposes of this project was to investigate conditions leading to the cracking in the oxygen cutting of rolled homogeneous armor. It was demonstrated that with appropriate cutting procedures rolled homogeneous armor in plate thicknesses up to 3 in. could be oxygen cut without cracking. Large inclusions, shrinkage stresses in internal corners of small radii cuts, and residual stresses resulting from straightening operations were found to be responsible for cracking in oxygen-cut plate.[245]

Later work on this project was primarily devoted to a study of cutting, grooving, and gouging operations on heavy sections of cast armor. Again it was found that with appropriate procedures cast armor of 4 in. thicknesses could be cut, grooved, and gouged without cracking. Shrinkage stresses in internal corner cuts with radii less than 1 in., low ductility, and especially inclusions are the primary reasons for cracking in cutting or scarfing operations on cast armor. Recommendations for the cutting of rolled and cast armor were also prepared.[246]

Welding of Face-Hardened Armor and Boron-Treated Homogeneous Armor

Although the problems attendant to the welding of face-hardened armor were considered urgent during the early part of World War II, greater emphasis on shock properties with the resulting increase in the use of homogeneous armor somewhat reduced the importance of this subject. Three projects were initiated, however: a correlation project, NRC-16R (OD-74), Welding of Face-Hardened Armor, at Rock Island Arsenal; Project NRC-24 (OD-74), The Development of a Process for Manufacturing and Welding of Face-Hardened Armor, at the Buick Motors Division of General Motors Corporation; and Project NRC-30 (OD-74), Development of Processes for the Manufacturing and Welding of Case-Carburized Armor Plate from Non-Alloy Steels, also at the Buick Motors Division of GMC.

The work on Project NRC-16R showed that it was impossible to weld face-hardened armor of the high nickel-molybdenum type with complete freedom from cracking by any procedure in which weld metal comes in direct contact with the carburized surface. No difficulty was experienced in welding the uncarburized surface of this type of armor. Special procedures involving precladding were developed which resulted in satisfactory welds in this material.[247]

Work on Project NRC-24 was primarily concerned with the development of a machinable type of face-hardened plate by additions of boron in the form of special addition agents, such as Grainal, to a controlled hardenability carbon-manganese steel. Tests showed this material to be readily weldable, but difficulties were encountered in duplicating plate material which made the results rather inconclusive.[84]

In Project NRC-30, Manufacture and Welding of Case Carburized Armor Plate from Non-Alloy Steels, special attention was paid to the effects of boron and other alloying additions on ballistic properties and weldability of armor steel. It was apparent from this work, as well as that on Project NRC-29, Manufacturing and Welding of Homogeneous Armor Plate from Non-Alloy Steels, that boron does not materially affect the weldability of armor. It is to be noted that some of the reported developments seem unsuited for welded applications.[85,86,106,107]

The above-mentioned projects dealing with boron-treated steels are also discussed in Sections 2.3.1 and 2.3.2, because they were concerned principally with the development of armor plate rather than with the welding of such plate, although the latter is an important consideration in its fabrication.

Stress Relief of Weldments

Shortly after the start of the armor welding program, research was initiated to determine the stress relieving characteristics of steels used in the fabrication of ordnance equipment, such as gun mounts. Investigations in this field were established at Ohio State University under Project NRC-3 (OD-34-2), Stress Relief of Weldments for Machining Stability, and at Rock Island Arsenal under Correlation Project NRC-17R (OD-34-2), Stress Relief of Welded Joints. In both these projects the variables present in stress relieving low-alloy steels and methods of measuring residual stresses were investigated. In addition, the problem of dimensional stability after machining was given special attention in Project NRC-3. These investigations indicate that (1) a temperature of at least 1100 F is necessary to eliminate effectively residual stresses in alloy steels, (2) temperature is more effective than time in reducing residual stresses, (3) thermal stress relief just below the critical temperature greatly improves

the stability of weldments after machining, and (4) both the magnitude of residual stress and the distortion which occurs on machining weldments in the as-welded condition are proportional to the yield strength of the steel at stress relieving temperature.[248-250]

Repair of Cast Armor by Welding

During 1944 the problem of repairing heavy cast armor became of extreme importance because of the need for heavy tanks. As a result of a request of NDRC initiated by the Office of the Chief of Ordnance-Detroit for the extension of Army Ordnance problem OD-36-2 to include the development of suitable electrodes for repair purposes, the programs of both Project NRC-1 and Project NRC-2 were modified to carry on this additional work. The basic problem was to develop a weld metal which when heat treated in accordance with the procedures used for heavy armor castings, would provide shock and penetration-resisting properties equivalent to heat-treated cast armor. Under Project NRC-1 at the United States Steel Corporation Research Laboratories, the objective was to recommend electrode compositions which, when deposited and heat treated, would develop fully martensitic structures at the center of 6-in. sections and to evaluate the suitability of these electrodes for the intended purpose. It is believed that the presence of tempered martensite or certain low-temperature bainites is essential to the development of good shock-resisting properties, and it was desired that these properties be realized at the highest practical hardness level in order to obtain adequate resistance to penetration by armor-piercing projectiles.

The work under Project NRC-2 at the Combustion Engineering Company was designed to produce and investigate the welding characteristics of electrodes recommended for the above purposes. It was necessary to terminate work on both phases of this investigation before it had been carried to a logical conclusion and as a result only preliminary work is reported. Several electrodes were developed, however, which appeared promising for the intended purpose.[217,218,251,252]

During the production of combat vehicles with heavy cast armor, considerable aid was furnished production foundries by members of the welding supervisory staff of the War Metallurgy Committee in the form of field service and consultation on repair welding problems. It is noteworthy that it was necessary to use the NRC-2A electrode, developed in the NDRC welding program, for the production repair of armor castings pending the development of better electrodes. All other commercial ferritic and austenitic electrodes were found to be unsuited for this application in Army Ordnance Department tests. The availability of this electrode undoubtedly speeded heavy tank production at a critical period. It is felt that this field service was one of the more important contributions of the War Metallurgy Committee and NDRC during the later stages of World War II.[253]

Development of an Electrode for Welding High-Strength Structural Steels

Another problem of considerable importance during the late stages of World War II arose because of the necessity for weight reduction in ordnance equipment. Experimental designs for gun mounts, tank transporters, etc., have been proposed using quenched and drawn steels of 90,000 psi minimum yield strength. The use of heat-treated steels in the 120,000 psi yield strength range has also been contemplated. As a result, there was an urgent need for the development of usable lime-coated alternating-current ferritic electrodes possessing equivalent yield strengths for fabricating these materials. However, these steels are essentially the same as those used for light homogeneous armor and, therefore, weldability problems are similar.

At the request of the Ordnance Design Sub-Office, Franklin Institute, the Office of the Chief of Ordnance requested NDRC for an extension of the scope of problem OD-36-2 and for this purpose a development program was added to Project NRC-76, Development of Improved Electrode Coatings, already being conducted at Battelle Memorial Institute. Although work on this project was terminated before the completion of the proposed program, two very promising electrodes were developed possessing 90,000 and 120,000 psi yield strengths with good ductility.[254] Additional work to determine the suitability of these electrodes for use under severe loading conditions is essential before definite recommendations can be made for their use in high-strength, lightweight structural applications. Important field service and consultation in connection with this general problem was also furnished the fabricators

of experimental equipment by members of the welding supervisory staff of the War Metallurgy Committee.[253]

6.1.3 Weldability

Although a fundamental study of the weldability of steels was not considered as important early in World War II as a more direct approach to special subjects, such as the armor problem discussed in the previous section, it was felt that information which would enable the selection of optimum arc welding conditions for steels used in the fabrication of tanks, gun mounts, and other ordnance equipment would be extremely useful. Because of the breadth of the general weldability problem, however, it was deemed desirable to limit initial studies to a particular phase of the subject in order to reduce the number of variables under simultaneous consideration. Since it was the considered opinion of many in the welding industry that the production of a ductile metallurgical structure in the heat-affected zone of the base metal was of paramount importance in avoiding welding and service difficulties, early work was restricted to a study of the effect of welding conditions on the heated base metal adjacent to welds and the utilization of this information to select welding conditions for different steels. In recognizing the significance of this aspect of weldability, it was not intended to minimize the importance of the electrode deposit, since it is apparent that the interrelation of both base metal and weld metal properties determine the subsequent behavior of the weld in service.

It is of particular interest to note the belief in 1942 that high ductility in the heat-affected base metal was essential to avoid such welding and service difficulties as cracking and poor ballistic properties. This conception undoubtedly was prompted to a great extent by the cracking observed in the heated region adjacent to welds made in hardenable steels which were made by using ferritic electrodes without preheat. Since that time, the underbead cracking phenomenon has been explained.[255] The relatively poor shock properties of the highly ductile elevated temperature transformation products has been demonstrated, as well as the fact that ductility measurements do not provide a valid method for predicting service performance particularly under severe loading conditions.[233] The results of the initial weldability investigations, which are briefly summarized below, should therefore be reviewed in the light of more recent findings.

Both the properties and structures of the base metal adjacent to the weld are necessarily influenced by a number of factors. It was believed that the most important of these were the rate of cooling of the heated base plate material and the hardening characteristics of the steel under consideration. Therefore, the first phase in the investigation of the effect of welding conditions on the heat-affected base metal involved the determination of the rate of cooling in this region. This was approached by making direct measurements and hardness measurements. Both lines of attack were resorted to, since it was realized that great difficulty was associated with the direct measurement of welding cooling rates and the subsequent extension of this data by mathematics to include a wide variety of conditions.

The method of attack utilizing hardness measurements was followed in Project NRC-9 (OD-37-1), Evaluation of Weldability by Direct Welding Tests, established at Lehigh University in April 1942. The procedure used involved the determination of the maximum hardness in the heat-affected base plate for given energy inputs, plate thicknesses, and joint designs, and the further relation of this hardness to the hardness of a standard end quenched Jominy hardenability bar of the same steel treated to reproduce the austenitic grain size found adjacent to the weld. It was assumed that corresponding hardnesses in the heat-affected zone and in the Jominy bar would represent equivalent cooling conditions, and in this manner welding conditions could be expressed in terms of Jominy positions. By heat treating to various hardness levels notched bend specimens from the material to be welded, the relative ductility corresponding to these hardness levels can be obtained from measurements of the angle at maximum load during slow bend tests of these specimens at room temperature. Thus, cooling rates could be correlated with ductility by relating both of these factors to hardness, and the selection of welding conditions to be used under given circumstances then resolves itself into a specification of the required ductility, which is a matter of experience and judgment.

To reduce the amount of experimental work necessary to provide working charts from which information applicable to a wide range of welding

conditions (current, arc voltage, and travel speed), plate thicknesses, and joint designs can be obtained, the assumption was made and verified that the cooling effect of various weld geometries can be related to the cooling effect exerted by metal within a certain distance of the weld. With the charts prepared in this manner, a quantitative prediction of the cooling rate for any combination of welding conditions, plate thicknesses, and joint design may be made without experiment. Then with hardness-ductility relationships established for the steel under consideration, welding conditions may be selected to obtain the desired ductility in the heat-affected zone adjacent to the weld.[256,257,258]

A program to undertake actual measurement of cooling rates in the heat-affected zone immediately adjacent to welds was established in March 1942 at Rensselaer Polytechnic Institute under Project NRC-10 (OD-37-1), Evaluation of Weldability by Direct Measurement of Cooling Rates. In this investigation, experimental techniques were developed to measure cooling rates associated with different welding conditions. The experimental data obtained were extended by means of mathematics to include a wide variation in welding conditions through modifications of the transient heat flow equations. The cooling rate data so obtained may be applied to particular steels for the purpose of securing any desired metallurgical structure adjacent to a weld through the use of the end-quenched Jominy hardenability test and isothermal transformation data. Procedures for applying this information to the solution of welding problems were developed.[259]

Another investigation, closely related to the above studies, was initiated for the purpose of studying the mechanism of heat flow during arc welding. This investigation, which did not involve any consideration of the metallurgical aspects of the problem, became Project NRC-11 (OD-37-1), Evaluation of Weldability by Correlation of Electrical and Heat Constants, established at Columbia University in April 1942. The investigations were conducted using the method of electrical analogy in which electrical networks are used which follow the same mathematical laws that apply to transient heat flow. General cooling curves were established for a variety of welding conditions and were found to be in close agreement with cooling curves determined by direct thermal measurements. An interesting and important feature of the electrical analogy method is that experiments need not be carried out in the same time in which the heat transfer phenomenon occurs. The time for the electric experiment may be made shorter or longer than the actual interval of heat flow on a scaled basis, which simplifies the procedure used for making measurements. Although the data accumulated in this investigation are incomplete, the validity of the method is evident and in all probability it may be applied to other welding problems involving transient heat flow.[260]

Under Project NRC-65 (OD-123), Evaluation of Factors Affecting Crack Sensitivity of Welded Joints, a research program was conducted at Rensselaer Polytechnic Institute. The principal emphasis of this investigation was placed on a study of the effects of the length of weld, plate thickness, plate composition, electrode, and welding variables upon the stresses produced. Welds were made using both transverse and longitudinal restraint, and considerable information was obtained for each case.[261] Another phase of this project was concerned with the magnitude of the stress at which cracking occurs in welds made under conditions of restraint. This condition is referred to as the cracking limit and comparisons were made to determine the significance of plate thickness, joint geometry, and type of electrode. The results of a limited number of comparisons made using comparatively thin plates indicate that the cracking limit is obtained at a stress value in the weld surface of approximately 80 per cent of the ultimate strength of the deposited metal, and that the shape of the cross section in the weld deposit significantly affects the cracking tendency in first pass deposits. These data were obtained using E-6020 and E-6010 electrodes in welds made in ½-in. plate without backing strips. Different results were obtained for welds made with backup bars.[262]

Another investigation conducted at Lehigh University, Project NRC-66, Methods of Testing Weldability of Steel Plates and Shapes, developed a method for quantitatively comparing the degree of restraint at which a weld cracks during cooling in steel plates of various compositions when all other conditions are maintained constant. A special fin-type specimen in which the restraint can be varied was designed for this purpose. Variations were noted in the cracking tendency of several plain carbon and low-alloy steels, and it was found that the test

method could be used to compare electrodes, in terms of the restraint at which cracks occur, with any chosen plate composition.

An investigation of the cracking tendency of several grades of commercial electrodes using the fin-type weldability specimen revealed differences in the quality of these electrodes. A study of the effect of preheat indicated that crack sensitivity is reduced proportionately as the plate temperature is raised.[263]

6.1.4 Resistance Welding

Several nonrelated resistance welding research programs were undertaken as needed to provide information considered necessary for the successful fabrication of war material, particularly aircraft. This work included investigations of the spot welding of light armor and alloy steels, the flash welding of aircraft steels, the spot welding of magnesium alloy sheet, and nondestructive test methods for spot and flash welds. Although fundamental data of major importance resulted from this work, it appears desirable to point out that these studies are representative of only a small portion of wartime resistance welding research.

Spot Welding

Investigations conducted prior to World War II indicated that spot welding offered a promising method for joining steels up to ½ in. in thickness. The possibility of fabricating light armor and alloy steels in this thickness range offered interesting possibilities and was made the subject of an investigation at Rensselaer Polytechnic Institute under Project NRC-12 (OD-85), Spot Welding of Armor Plate and Low-Alloy Steels. Attempts to utilize early information led to a complete investigation of the fundamentals of spot welding heavy plate, together with an investigation of the feasibility of heat treating spot welds in the welding machine. As a result of this work, which included the development of control equipment, measurement techniques, and a test for weld properties, a general procedure was formulated which permits the selection of optimum welding and heat-treating conditions to be used for any given thickness combination of hardenable steels. Procedures were also developed for spot welding alloy steel clip attachments to both homogeneous and face-hardened armor. In ballistic tests these weldments demonstrated shock resistance properties equivalent to the armor itself. An interesting comparison of the merits of continuous and pulsation welding for this application showed that the continuous process is to be preferred.[264,265]

To ascertain the feasibility of predicting weld strengths from radiographic or fluoroscopic images, Project NRC-56, Radiographic and Fluoroscopic Methods of Inspection of Spot Welds in Aluminum Alloys, was established at California Institute of Technology in March 1943. In this investigation, a new short source-film-distance technique was developed for spot-weld radiography which enables determinations of weld structure and quality to be made and also provides a consistent and positive method for determining the strength of spot welds made in Alclad 24S-T and XB75S-T sheet in equal or unequal thickness combinations up to a ratio of 3:1.[266] As this technique involves the unorthodox procedure of placing the X-ray tube very close to the film, it is applicable only to the radiography of thin specimens. The interpretation of spot-weld radiographs given in the final report on this project was adopted and included in the Navy Bureau of Aeronautics Specification PW-6A, Amended, covering spot welding process control and inspection for naval aircraft.

A study of the fluoroscopic method of spot-weld inspection showed that further development, including a major improvement in screen contrast and definition, was necessary in order to attain the reliability and accuracy exhibited by the radiographic method. In general, those aluminum alloys with high percentages of radiographically dense alloying constituents, such as zinc and copper, will produce spot-weld images which may be used for process control, whereas alloys without dense constituents cannot be handled in this fashion.[267]

The feasibility of spot welding magnesium alloy sheet material was investigated at Rensselaer Polytechnic Institute under Project NRC-68, Spot Welding of Magnesium Alloys. It had been demonstrated in early studies that for the production of sound and consistent spot welds the surface of the sheets to be welded must be carefully prepared either chemically or mechanically. Therefore, a major objective of this investigation was to develop a single chemical solution which would clean all varieties of magnesium sheet at room temperature.

As a result of extensive work on this aspect of the problem, a chemical method for preparing magnesium sheet for spot welding was developed. The solution used contained 10 per cent chromic acid with an addition of 0.05 per cent anhydrous sodium sulphate.[268]

Since magnesium alloys are similar to aluminum alloys in that they have relatively high electrical and thermal conductivity and low melting points, the essential requirements in equipment and technique for spot welding magnesium alloys are similar to those required for aluminum alloys. Optimum conditions for spot welding equal thicknesses of three commercial compositions of magnesium alloy sheet in several tempers and thicknesses were determined and are presented in the final report on the project together with a description of methods used for testing and examining spot welds in these alloys.[269]

Flash Welding

Project NRC-13 (OD-86), Flash Welding of Alloy Steels for Ordnance, was established at Battelle Memorial Institute in April 1942.

In order to investigate the effect of process variables on the production of high-quality welds, differences resulting from varying the electrical and mechanical factors associated with the process were appraised by metallurgical examination and mechanical tests. It was demonstrated in the investigations that high-quality flash welds made in SAE-4130 steel heat treated to 160,000 psi are as strong as the parent material. Defective welds resulted from decarburization at the weld interface and the presence of oxide films at this location.[270-274]

Attempts were made to eliminate these defects by surrounding the flashing surfaces with nonoxidizing atmospheres during welding. Dry hydrogen, dry carbon monoxide, and natural gas were shown to have possibilities as protective atmospheres. The results of these tests show that defects are obtained even with these atmospheres, if the electrical or mechanical conditions are not properly established. It was noted, however, that the variation in welding conditions which can be tolerated without affecting the production of high-quality welds is greater when the protective atmospheres are used.[275]

Part of the activity of this project included the translation of the German book by Hans Kilger, published in 1936, which discusses the fundamentals of the flash welding process.[276]

The difficulty of determining the quality of flash welds in production without resorting to destructive tests led to the establishment at California Institute of Technology of Project NRC-57 (OD-86), Non-Destructive Testing of Flash Welds. Among the many methods investigated, four were found which may be used with limitations for the detection of flash-weld flaws. These methods include the standard magnetic powder test and several special tests.[277-279] Of these tests, one in which the deviations from a normal eddy-current flow pattern in the region of the weld are measured is considered to offer the greatest possibility for production testing. In this test, deviations in the eddy-current pattern are produced by flaws in the weld. It is of particular interest to note that the eddy-current test may be successfully applied to the testing of nonferrous metals.[280]

To determine the research needs in the field of aluminum alloy flash welding, Survey Project SP-23, Flash Welding of Aluminum, was carried out by the War Metallurgy Committee in mid 1944. This survey showed that the application of this process to aluminum alloys was in its infancy. No standardized welding techniques existed, and there were considerable differences of opinion regarding proper methods for welding and the design of machines. On the basis of rather inconclusive evidence, it appears that it may be possible to produce flash-welded joints possessing 90 per cent of the tensile strength of the parent alloys. From expressed opinions, it is believed that most aluminum alloys can be successfully flash welded and that heat treatment after welding will probably improve the joint properties in certain compositions.[281] No NDRC research projects were established on this subject.

6.1.5 Indexing of Division 18 Reports on Welding of Armor and Ordnance

An index of the Division 18 reports on the welding of armor, ordnance steels, and structural steels issued during the period 1942 to 1944 was prepared by the Research Information Division of the War Metallurgy Committee. This index[282] gives a subject list of the various projects with the reports issued on each, a brief abstract of the contents of each

report, and a subject index of the reports. It lists also the steels and electrodes used in the investigations.

6.2 SHIP WELDING AND WELDED STEEL SHIPS

6.2.1 Introduction

Several welded tankers and dry-cargo ships suffered severe structural failures during the winter of 1942-43. Failures occurred both at sea and when ships were moored in quiet harbors. These failures were of the brittle cleavage type and often propagated with explosive rapidity, in some cases the reports having been heard as far as a mile away. The fractures which started at discontinuities in the hull structure occasioned by fabrication and design traveled transversely across the hull structure, in several instances splitting the vessel in two.

At the outset of the extensive war shipbuilding program of the Merchant Marine, it was decided that the ships were to be fabricated by welding. Although the experience available at that time bearing on the operation and fabrication of welded ships was limited, it was decided to adopt this method of construction rather than riveting because welding reduced greatly the construction time and saved materials. Both of these factors were, of course, of paramount importance.

Investigations following these hull failures revealed the fact that, although in many instances the workmanship was not satisfactory, the shipbuilding materials complied with the existing specifications. Recognition of the seriousness of faulty workmanship led to immediate improvements through education and extended supervision and inspection.

At that time it was the considered opinion of the majority of technical shipbuilding personnel that a prime factor in the cause of these failures was the existence of residual stresses locked in the hull structure generally, but particularly in the welds and adjacent material. This opinion was based on the appearance of cracks parallel to the weld which occurred when a weld was made under high restraint and the proper welding sequence had not been followed. These cracks were believed to be caused by high transverse stresses resulting from the welding operation. It was also believed that such high transverse residual stresses were present to a degree in all welds and when they were combined with the working stresses of the hull, particularly at welded butts, hull fractures resulted. For this reason great emphasis was placed on following a prescribed welding sequence in order to avoid or at least minimize residual stresses. In consequence, when the research program for investigating the structural failure of welded ships was started, prime emphasis was placed on a study of welding stresses.

Through the recommendations of the War Metallurgy Committee and with the cognizance of the U. S. Maritime Commission, the U. S. Coast Guard, and the American Bureau of Shipping, NDRC had established the first research project in this general field by June 1943. As time went on, the need for investigating the ship failure problem from other viewpoints became apparent. This resulted in the establishment of additional research projects so that by August 1945, fifteen investigations in this field were in progress, or had been completed.

6.2.2 Welding Stresses in Ship Construction

Two research investigations were established at the University of California to investigate welding stresses. Project NRC-64 (NS-304), Residual Stresses in Ship Welding, was concerned with studies of residual stresses in typical ship weldments as well as those in actual ship subassemblies, while Project NRC-74 (NS-305), History of Residual Stresses in Welded Ships, dealt with investigations of both residual stresses in actual ship subassemblies and the locked-in stresses in the hull structure of completed ships. Residual stresses are defined as the welding stresses produced in free subassemblies, while locked-in stresses include also the stresses resulting from other fabrication and assembly processes.

The research projects to study residual stresses were organized to determine the magnitude and distribution of stresses in typical ship weldments, etc. To determine these stresses, a method of relaxing plugs containing resistance strain gages was perfected. Weldments consisting of 1-in.-thick ship plates and ranging in size from 4-ft by 6-ft to 27-ft by 57-ft ship subassemblies were investigated[283,284] The effect on the magnitude and distribution of residual stresses was determined as a function of such variables as manual and Unionmelt welding,[285] welding sequences,[283-286] electrodes,[221-223,284] restraint,[285,286] preheating,[285,286] peening,[283,286] me-

chanical loading along a butt weld,[284] and the effect of controlled low-temperature stress relief.[286]

The investigation of the locked-in stresses in completed ships, Project NRC-74, was organized to determine: (1) stresses in the decks of six recently completed vessels and eight ships that had been in service,[287] the history of the changes of the locked-in stresses starting from completed deck subassemblies and tracing these stresses through construction, launching, outfitting, and loading, as well as during the first voyage of two Liberty ships;[288] (2) the effect on the locked-in stresses of the hogging and sagging test of three type T-2 tankers;[289,290] (3) the stress effects owing to temperature gradients through the hull structure;[291] (4) the magnitude and distribution of locked-in stresses in the decks of 21 Victory ships constructed in three Pacific Coast yards;[292] the stress effects of welding a large hot deck subassembly into a cooler hull structure;[293] and the use of X-ray diffraction measurements for determining stresses in hot-rolled plate.[294,295]

Some significant conclusions from these investigations are as follows:

1. The magnitude and general pattern of the residual welded stresses existing in very large weldments up to 27 ft by 57 ft can be obtained in panels as small as 6 ft by 4 ft. These stresses are sufficiently reproducible either by Unionmelt or manual welding to enable significant effects of different controlled variables to be determined.[283,284,286]

2. In butt welds of free subassemblies made from 1-in. plate, the longitudinal residual stresses along the center line of the weld reach a magnitude of approximately 47,000 psi in tension throughout the length, except in the 9 inches adjacent to each end where they decrease to zero at the ends. The transverse residual stresses are low tension usually less than 10,000 psi, except near the ends of the weld where they change to compression, reaching values of from 20,000 to 30,000 psi at the ends.[276,283,285,286]

3. Welding sequence in general does not affect the magnitude of residual stresses in free subassemblies.[286]

4. Longitudinally along the deck welds of completed Liberty ships[a] stresses were tensile and ranged from 20,000 to 50,000 psi with an average value of 36,000 psi. Stresses transverse to the welds reach a maximum value of 11,000 psi in tension with an average value very close to zero. It was determined also that these stresses are not reduced appreciably by normal service[287] since only a very small fraction of the welded ships have failed. Therefore, it was concluded that the locked-in stresses do not contribute materially to such failures. Similar investigations on board C-4 troopships[290] and T-2 tankers[288,290] also were completed.

5. The locked-in stresses at selected points away from welds in the general deck area abreast of a No. 3 hatch of completed Liberty and Victory ships are generally compressive.[287,292] In the Liberty ships, the locked-in stresses ranged from 1,500 psi in tension to 9,800 psi in compression with an average value of 5,200 psi in compression.[287] In the Victory ships these locked-in stresses range from 8,800 psi in tension to 16,600 psi in compression with an average value of approximately 7,600 psi in compression. Those near the gunwales of completed Victory ships are generally tensile and reached a maximum value of 5,900 psi. Higher values of locked-in tensile stresses were observed at other locations in the deck.[292]

6.2.3 Effect of Multiaxial Loads on the Behavior of Ship Steel

As the investigations dealing with welding stresses progressed, it became apparent that these stresses were not important factors contributing to the structural failure of welded ships and that other phases of the problem should be investigated.

Upon review of the brittle characteristics of fractured material removed from ships that had failed, questions were raised regarding the state of stress to which this material had been subjected. It was felt that the hull steel must have been subjected to a complex state of stress since, as manifested by the low degree of ductility exhibited by the fracture, shear flow had been inhibited. When samples of steel taken close to the fracture were subjected to the usual tests, they exhibited satisfactory strength and ductility.

In order to study this problem, two research projects were initiated early in 1944: Project NRC-75 (NS-306), Behavior of Steel under Conditions of Multiaxial Stresses and Effect of Welding and Temperature on this Behavior, at the University of California; and Project NRC-77 (NS-307), Behavior of

[a]The computed tensile deck stresses resulting from the bending moments were essentially the same in all ships ranging from 2,200 psi to 4,700 psi with an average value of 3,400 psi.

cleavage fractures of very low ductility occur, the fracture strength of the material is less than its yield strength. In the type of fracture encountered in welded ships, the yield strength has been raised owing to the complex state of stress existing at the root of the fracture and the high strain rate. A method for separating these increments to the yield strength is not known. Subsequent investigations may show an equivalence between the effect of strain rate and state of stress on the yield strength comparable to the apparent relationship between strain rate and temperature. So far the explosion test appears to be the only method whereby strain rates of the order of those probably obtaining in ships during fracture can be achieved.

Under Project NRC-72, Investigation of Factors Reducing the Effective Ductility of Welded Steel Members, at the Massachusetts Institute of Technology, sufficient work has been completed to confirm an apparent equivalence between temperature and strain rate recently promulgated.[80] This work was done using welded and unwelded-notched beam specimens, 1 in. by 1 in. by 6 in. in size, of several ship steels. The temperature was varied from +480 to −280 F, and the testing speed to reach the yield point was varied from 0.05 second to 5 minutes. The investigation is being continued under the sponsorship of the Welding Research Council.

The direct explosion test developed by the Trojan Powder Company under Project NRC-25 (OD-76) (NS-255), Direct Explosion Test for Welded Armor and Ship Plate (see also Sections 2.2 and 6.1.2), appears to be a most promising method for determining behavior of specimens, welded and unwelded, under high strain rates. Using plates approximately 12 in. square, an essentially equal biaxial tensile stress can be produced on the tension face. This biaxial stress is accompanied by a third axial tensile component of unknown magnitude and phase relationship. Thus, it is possible to test plate specimens under triaxial stress and high strain rates and, in addition, the temperature may be varied. Special explosives have been developed whereby the velocity of the detonating wave and the gas volume can be controlled. It is possible thereby to vary the shock loading so that the specimen can be fractured without spalling on the tension face. This was considered necessary, since it was desired to fracture the steel on planes normal to the plate surfaces, but at the same time keep the third-axis stress component as large as possible in order to maintain a high degree of restraint. Preliminary investigations have evaluated shipbuilding and HT steels in the same order as predicted by the Charpy impact test.[309] Essentially the same results have been obtained from similar specimens subjected to a static-bend test at low temperatures.[310]

This investigation is still in progress under a direct contract with the Bureau of Ships, Navy Department.

6.2.6 Weldability of Hull Steel

At the specific request of the Office of the Coordinator of Research and Development, Navy Department, two investigations, Project NRC-86 and Project NRC-87, were established in May 1944 to study the factors influencing the weldability of hull steels and to determine the relation between these factors and the metallurgical quality of the steels.

Project NRC-86 (NS-255), Weldability of Steel for Hull Construction, at Lehigh University, utilized a restraint test which was found useful in predicting the behavior of steels and electrodes in the fabrication of welded structures. Through this test, undesirable heats of HT hull steels could be segregated by determining their sensitivity to cracking when welded under various degrees of restraint.[311] The investigation involved a study of such variables as the variation of steel composition, variation of chemistry within a given specification, effect of position in the ingot, variation among steel suppliers for a given specification, effect of electrode, preheat, plate thickness, and edge preparation.

This project made also a preliminary study[310] of the factors, such as metallurgical structure, temperature, residual stresses, and stress concentration (notches), that are believed to affect the ductility of welded joints. The program included static-bend tests, notched and unnotched, in which the specimens were bent both longitudinally and transversely to the welds. An extensive investigation of the Charpy impact values at various positions in the weld heat-affected zone and parent plate was started in an attempt to explain the influence of each on the behavior of the plate as a whole in the bend test.

Under Project NRC-87 (NS-255), Investigation of the Metallurgical Quality of Steels Used for Hull Construction, conducted by Battelle Memorial In-

stitute, the factors influencing underbead cracking of HT steel were studied. A weld-bead test was developed to measure this tendency. This test indicated large differences in crack sensitivity of various lots of the same grade of steel. Frequent variations of crack sensitivity were found that could not be explained on the basis of chemical analysis, end-quench hardenability, hardness of the heat-affected zone or tensile properties. The crack sensitivities could be changed markedly by heat treatment. This investigation also included a study of the steel making and processing procedures used in making commercial heats of this grade of steel and involved the determination of crack sensitivity effects of plate thickness, position in the ingot, grain size, microstructure, and tensile properties.[312-315]

Since these projects are being continued under direct contracts with the Bureau of Ships, Navy Department, only tentative conclusions can be drawn at this time. The following appear significant:

1. Satisfactory correlation exists between the behavior of four heats of HT steel as predicted by the restraint test[310] and the direct explosion test.[309] Both prime plate and double-V butt joints welded with E-6010 electrodes were tested.

2. The transition temperature for the prime plate is lower than that for the welded plate in all cases where prime plate properties have been compared with welded plate properties in the as-welded condition by the static-bend test. The steel compositions investigated included a 0.18 carbon steel, a 0.25 carbon killed steel, and an HT (0.18 per cent) carbon steel; the electrodes used included the E-6010, HTS, and 25-20 types. It is believed that this bend test can be used to determine the influences of such factors as metallurgical structure, dissolved gases, and residual stresses on the ductilities of welded joints.[310]

3. The relative tendency toward underbead cracking of HT hull steel can be determined by a simple weld bead test made under closely controlled conditions.[313-315]

4. Higher compositions have generally greater sensitivity to underbead cracking. However, variations in the crack sensitivity of different lots of HT steel occurred frequently. These variations could not be explained on the basis of chemical analyses, hardenability, hardness in the heat-affected zone, or other properties commonly determined.[313-315]

5. Thermal treatment was indicated to have a pronounced effect on crack sensitivity. Homogenizing decreases and annealing increases this sensitivity.[314,315]

6.2.7 Fatigue of Ship Welds

On a number of ships, hairline cracks have been observed in the vicinity of the hatch corners. Owing to the stress concentration in this area occasioned by the hatch corner discontinuity, it appeared reasonable that these could be fatigue cracks caused by the alternating loads to which a ship is subjected in a seaway. These cracks would then propagate until the stress in this area had been lowered by the reduction of the stress concentration factor. Upon subsequent loadings having higher stress amplitudes and increased strain rates, for instance, in a rough sea with a lowered temperature, it was expected that, owing to the lowered notch toughness, the hairline crack could act as a trigger to start a fracture propagating through the structure.

Welded ships have suffered structural failures after only a short period of sea service or with no service at all. It appears, therefore, that while fatigue failure may be a contributing factor, it does not provide an adequate explanation for the structural failures of welded ships.

Project NRC-89 (NS-304), Fatigue Tests of Ship Welds, was established at Cornell University to determine the fatigue behavior of ship steel specimens containing longitudinal welds and cutouts with and without welded reinforcement plates and doublers. No significant conclusions can be drawn as yet owing to the limited amount of work completed.[316] This investigation is being continued under a direct contract with the Bureau of Ships, Navy Department.

6.2.8 Status of the Research Program

Since most of the above-mentioned investigations are still in progress under the sponsorship of the Bureau of Ships, Navy Department, no evaluation of the results can be given at this time. However, it appears reasonable to anticipate that the completion of these projects will assist in determining the relative importance of the design, material, and fabrication method in the successful service performance of welded ships. Thus, it is anticipated that the results

of this research program will ultimately be of considerable assistance in the design and construction of low-cost welded ships of assured service performance. This background information will be of particular value in the future construction of welded passenger ships where even minor structural failures may have most serious consequences.

Most of the Division 18 projects, which have been taken over under direct contracts by the Navy Department, are being continued for the present under the supervision of the War Metallurgy Committee. The objective of these projects is to obtain additional experimental data upon which definite recommendations bearing on the problem of the design and construction of welded ships can be based. This work will involve:

1. Obtaining additional data to explain more fully the reasons for the reduction of the strength and ductility of welded structures, especially at low temperatures or high-strain rates, by means of (a) investigations of the large as-welded tubes (20 in. in diameter, 3/4-in. wall) subjected to biaxial tensile stresses, especially when tested at low temperature (−40 F), and (b) bend tests of unnotched plates containing a butt weld or surface weld bead and subjected to the explosion test or a static-bend test at low temperature.

2. Performing additional tests on steels of superior notch toughness using large flat plate and hatch corner specimens.

3. Investigating improved hatch corner designs.

4. Continuing the investigation to determine the fracture stress at zero ductility of steel in an attempt to explain the factors, particularly from the viewpoint of metallurgy and mechanics, which control the change from shear to cleavage type fractures.

5. Attempting to develop a laboratory test to predict the service performance of large structures.

6. Obtaining information relative to the fatigue behavior of typical ship welds.

Chapter 7

FOUNDRY MATERIALS AND PROCESSES

7.1 MALLEABLE IRON

Early in World War II steel-making facilities were often overloaded with orders for cast steel products as the demand far exceeded the capacities of the industry. It became apparent that, if malleable iron could be used in war material applications where steel had been used, the large productive capacity of the malleable iron industry would be available to the war effort.

When substitution of malleable iron for cast steel in tanks, combat vehicles, and other military applications is contemplated, a question arises as to its behavior at low temperatures and at elevated temperatures. While experience in other uses indicates that, over the range of temperature involved, malleable iron does not depart greatly from its room-temperature behavior, more information was needed. To explore this possibility, the Ordnance Department requested, under their control number OD-81, that the effects of temperature on the properties of malleable iron be investigated. Therefore, Project NRC-28, Properties of Malleable Iron Castings for the Use in Tanks, Combat Vehicles, and Other Military Applications, was established at Battelle Memorial Institute. This project encompassed an investigation of the effects of low temperatures on the impact resistance of malleable iron castings by Charpy impact, tensile impact, and wedge tests on different grades of commercial malleable irons, pearlitic malleable irons, and cupola malleable irons over a temperature range from +75 to −50 F, and a study of the effects of elevated temperatures on the same variety of malleable irons by the same tests at temperatures up to and including 1200 F.

A comparison of the mechanical properties of ordinary grade B cast steel, normalized and drawn, with those of malleable irons, heat treated according to their class, is given in the following tabulation:

	Grade B cast steel	Malleable iron: Regular	Pearlitic	Cupola
Yield strength, psi	45,000-55,000 (0.2 per cent offset)	33,000-37,000	42,000-57,000	25,000-30,000
Tensile strength, psi	75,000-90,000	53,000-57,000	75,000-93,000	42,000-48,000
Elongation, per cent	25-35	12½-25	8-18	5-7
Reduction of area, per cent	30-55	20-25	5-15	4-7
Charpy impact (room temp.) keyhole, ft-lb	15-30	5-8	2-6	4-5
Charpy impact (−40 F)	1-20	3-7	1-3	3-4

Regular malleable is peculiar in that increased strength and increased ductility go hand-in-hand. With other ductile ferrous products, ductility decreases as strength increases.

Pearlitic malleable can be made with a yield strength closely approaching that of cast steel, but it has lower ductility. Regular malleable runs below cast steel in both yield strength and ductility, but, if the design in which substitution is to be made does not require all the yield strength of steel, or if the design is modified in accordance with the yield strength, it should be a usable material, for it combines a fair level of toughness and has long been used in many severe services, e.g., in railway parts and in trucks where it may have to resist shock and even battering. Cupola malleable, though made more economically than the other types, has a relatively low level of strength and ductility, although it serves well for some purposes, such as pipe fittings. All the malleables, especially regular malleables, are very readily machined having, in this respect, a material practical advantage over cast steel.

When comparing malleable with cast steel with respect to low-temperature behavior, it needs to be recalled that cast steel may show very low notched bar impact values at low temperature, as the cited range of 1 to 20 ft-lb at −40 F shows.

It is now well understood that within this range variations in cast steel are governed by the deoxidation practice. Thus, well deoxidized basic or acid open-hearth, basic or acid electric, and converter steels will give results hugging the top of the range. Poorly deoxidized steels made by any of these processes may hug the bottom of the range.

Not much attention has been paid to this, and much cast steel with very low notched bar impact resistance at subnormal temperatures has undoubtedly been in low-temperature service and given satisfactory service under conditions where the

designer, had he appreciated how brittle poorly made cast steel can be at low temperature, would have specified that the steel be tested for low-temperature toughness and that those heats of steels lacking in such toughness be rejected. That is, cast steels no more resistant to shock at low temperature in the presence of notches than the better grades of malleable, have given useful service. Neither steel nor malleable parts that are too severely notched will stand severe impact. Engineering design has to recognize this and see to it that where impact is involved severe notches are absent, and that where notches cannot be avoided the parts are protected from receiving severe shock by design of the assembly.

It is well known that the usually determined mechanical properties of both steel and malleable, with the exception of notch toughness or impact resistance, improve as the temperature drops within atmospheric temperature limits. Attention was focused, therefore, on the low-temperature impact behavior.

Tensile impact results on unnotched bars of all three types of malleable do not materially diverge, either in energy absorbed or in elongation produced, from room-temperature results, even down to –80 F. At least down to –40 F, the same was true of unnotched Charpy bars.

Cupola malleable did not prove promising for low-temperature use. Pearlitic malleable was somewhat more promising in view of its high yield strength, with fair low-temperature behavior, but regular malleable showed the best low-temperature behavior.

However, regular malleable should be so heat treated as to remove all vestiges of pearlite.

Notched bar impact tests are not so selective as the wedge-curl drop test, and wedge-curl drop tests at low temperatures seem indicated for proving that the heat and heat treatment have produced material that will be tough at low temperatures. If such testing is applied to eliminate material of doubtful quality, regular malleable can be selected that appears to have as good toughness at –40 F as at room temperature, and usable toughness at still lower temperatures.

At elevated temperatures, the best combination of properties in all irons occurred in the temperature range of 70 to 200 F. Above these temperatures and up to about 600 F, ductility either remained constant or fell off. Charpy impact values fell off continuously to about 1000 F, while wedge test results generally reached a low point at temperatures ranging from 400 to 800 F. Tensile impact values dropped steadily to about 800 F and the strength held up fairly well to 600 F, above which it dropped off rapidly while the ductility correspondingly increased.

The results of this investigation provided data[317,318] upon which the substitution of malleable iron for cast steel could be based in considering materials for various parts of war material in the expectation that such would divert a considerable tonnage from steel to the more plentiful malleable iron facilities. A summary of this work was published serially for the benefit of industry.[319]

7.2 CENTRIFUGAL CASTING

7.2.1 Survey of the Status of Centrifugal Casting

As malleable iron was substituted for cast steel in order to alleviate shortages in steel casting facilities, it was believed that castings, particularly steel castings, made by the centrifugal casting process might to some extent replace forgings and thus relieve the pressure on forging facilities. Conventional mass production facilities for the manufacture of forgings and seamless tubings were inadequate to meet the unusual demand and, because of the relatively small initial investment, centrifugal casting methods appeared attractive and promising. To determine the feasibility of this substitution, the War Metallurgy Committee carried out a survey of the status of development of the centrifugal casting process and of the possibility of extending its use to items of ordnance matériel. The applications, advantages, and limitations of the process were studied and, although the survey was not complete, it was adequate for the purpose of appraising the general problem and providing a basis for the formulation of a program of development. In the report on this survey,[320] five immediate needs were indicated and four projects were established. Subsequently, the Army Ordnance assumed active sponsorship of these projects under their control number OD-108.

7.2.2 Bibliography on Centrifugal Casting

This bibliography[321] was prepared by the Naval Research Laboratory under Project NRC-34N (OD-

108) in cooperation with the War Metallurgy Committee. The report consists of a short resumé of the centrifugal casting field, a discussion of the fundamentals of the various processes, brief abstracts of the more comprehensive writings on the subject, and a chronological, classified listing of publications and patents. It provided assistance not only to the groups engaged in centrifugal casting but also to those contemplating entering the field.

7.2.3 Heat Flow in Metal Molds

As recommended by the survey, Project NRC-33 (OD-108), Analysis of Heat Flow in Metal Molds for Centrifugal Casting of Gun Tubes, Airplane Cylinders, Tank Bogey Wheels, and Other War Matériel, was established at Battelle Memorial Institute with the objective of obtaining data which would permit improved designs of casting machines, increased life of molds, and improvements in cast product owing to accelerated and controlled heat abstraction.

The adoption of centrifugal casting in metal molds for production of steel gun tubes, aircraft engine cylinders, tank bogey wheels, etc., raises questions as to the proper material for molds and the proper thickness of the molds.

Molds could be made, for example, of steel, cast iron, or copper, with the first cost and ease of manufacture naturally in favor of cast iron. The molds can be thin or thick, with first cost and ease of spinning on the side of thin molds. The outside can be plain or corrugated and can be air cooled or water cooled.

Failure of molds usually occurs by heat checking, a result of repeated tensile stresses. The number of casts before a mold has to be discarded because of heat checking depends upon the magnitude of the tensile stress set up by the thermal gradient and upon the ability of the material to withstand repeated tensile stresses of that magnitude.

Fundamental information on the thermal gradients and resulting stresses was sought by elaborate experiments on steel, cast iron, and copper slabs of different thicknesses, cooled in various ways, when varying amounts of molten steel were cast upon them.

The results[322] showed that the stresses produced in the different materials are pretty much at the same level as their known ability to resist repeated stresses. This results from the differences in modulus of elasticity among the three materials. Water cooling does not seem to offer much advantage over air cooling.

Since the other materials do not appear outstandingly better than cast iron, the commercial use of cast iron for molds seems justified. While thin molds reach maximum temperature and maximum stress quicker than thick ones, thus giving less time for stress relief, the overall service, compared with cost, will probably be better for thin molds than for thick ones.

Marked improvement by lowering maximum temperature and maximum stress is afforded by a heat-insulating mold coating 0.04 in. thick. A coating of 0.01 in. in thickness is much less effective. Rather thin, air-cooled, cast iron molds with the 0.04-in. insulating coating appear at least as good an engineering choice as any other readily available mold material.

7.2.4 Mathematics Underlying the Process

Survey Project SP-10 (OD-108), Mathematics Underlying the Centrifugal Casting of Metals, was carried out by the War Metallurgy Committee, and the report was edited and revised by the Applied Mathematics Panel of the NDRC.

Centrifugal casting, not only of cylindrical objects but also of other shapes, involves forcing molten metal under pressure against the mold wall by centrifugal force. The pressure is usually expressed as "times gravity." The optimum pressure for any given setup is produced at some particular rotational speed. Mold inside diameter, casting thickness, density of metal being cast, rotational speed, and angle of inclination of the mold to the horizontal all enter as variables. It is premature to assume that an ideal rotational speed can at present be calculated or predicted because of the many variables concurrently operating and the lack of knowledge regarding the interrelationship of these variables. The report on the project[323] does, however, present information on the mathematics underlying the mechanics of metal spinning and is a practical manual by which the more obvious values of practical interest, such as times gravity and pressure on mold wall, can be determined and converted from one to the other by

means of handy charts. It also provides a common nomenclature for the use of those contemplating the adoption of the process.

7.2.5 Development and Extension of Centrifugal Casting Methods

Project NRC-26 (OD-108), Improvements in and Extension of Centrifugal Casting Methods for Production of Miscellaneous War Matériel Items, was established in the laboratories of the United States Pipe and Foundry Company. It involved application of centrifugal casting methods to objects ordinarily produced by other methods, but for which methods existing facilities were limited.

Seamless steel tubing was not in sufficient supply to provide the desired number of 60-mm trench mortar barrels and, at the request of the Philadelphia Ordnance District, centrifugal casting of such mortar barrels was studied.[324] Casting centrifugally in a steel mold preheated to about 350 F and sprayed with a water suspension of silica flour and colloidal bentonite produced tubes which, after rough machining, were free from visible defects and withstood the hydraulic pressure test. Heat-treated and machined, such tubes were found entirely satisfactory on overload proof-firing tests at Aberdeen Proving Ground. Casting details as to mold speed, mold temperature, refractory coating thickness, casting temperature, speed of pouring, etc., were then worked out.

The process was applied to the commercial production of 60-mm and 81-mm trench mortar barrels. This released for production of aircraft tubing the equipment for making seamless tubing that would otherwise have been required for trench mortar barrels. The cost of the centrifugally cast barrel is higher but production facilities, rather than cost, were the important feature of the situation that was thus met.

The success of this work led to a study of the casting of recoil cylinders for 90-mm and 105-mm guns[324] at the request of the Army Ordnance Department. These large castings, over 5 ft long, 6 in. OD, and 3½ in. ID in the rough, were made in cast iron rather than steel molds, carrying a refractory wash. Machining ¼ in. each from the OD and ID removed all casting defects and shrinkage, and recoil cylinders from the castings, after heat treatment, finish machining, honing and lapping, met all requirements of mechanical properties, machinability, and finishability.

Rock Island Arsenal reported[324] on these centrifugally cast recoil cylinders as follows.

> 1. The ten (10) centrifugally cast cylinders submitted by the U. S. Pipe and Foundry Company, Burlington, N. J., have been found to be suitable for processing into 105-mm recoil cylinders which meet all requirements and specifications, including physical properties, machining, honing, and lapping characteristics.
>
> 2. It is believed that, if cylinders can be produced by centrifugal casting which consistently show composition and physical characteristics similar to the ten (10) cylinders tested, an additional source of cylinder stock, other than those of bar stock and drawn tubing, can be developed by the method of centrifugal casting.

An attempt was made to produce steel recoil cylinders lined with monel metal to replace those made from solid forgings of monel.[325] This would have saved much critical monel metal. No successful bonding was accomplished by centrifugally casting monel metal into a heated steel tube, but good bonding was produced by pouring molten steel into the rotating mold first and following this, while the steel was still above 2500 F, with a pour of molten monel metal. Unfortunately, shrinkage voids in the monel metal produced small imperfections in the ID not permissible in recoil cylinders. As the use of monel metal for recoil cylinders had been abandoned by the time satisfactory bonding had been achieved, the problem no longer existed and no further attempt was made to produce duplex steel-monel castings with perfect interiors.

End connections for tank treads were cast[325,326] using several molds arranged radially about a central pouring gate, and using special dry sand mixes to avoid cutting the mold by the molten metal. Centrifugal force was used to flow the molten metal into the molds. After working out the proper gating, radiographically sound castings were made and supplied to the Army Ordnance Department for heat treatment and service test. Early fracture of some of the castings brought out the fact that the heat treatment applied by the Ordnance Department was quenching without tempering, the Brinell hardness being 500 instead of the specified 330 to 375. The Army Ordnance Department planned to temper the castings properly and run them to destruction, but apparently this was never done because adequate forging facilities had been provided by that time. From the analogy of other cases, one would expect that, had the test been made, the centrifugal castings, correctly

heat treated, would have proved serviceable.

X4130 steel for seamless tubing for aircraft is normally cast into ingots, rolled to blooms, the blooms reheated and rolled into rounds, and the rounds pierced in a tube mill. All this processing to produce a hollow round for subsequent rolling and drawing could be obviated by centrifugal casting of a hollow round billet in the first place. This was done[325,326] and the centrifugal billets hot rolled and drawn. No difficulty was met in these operations.

However, no boring or broaching was done on the ID of these hollow cylinders, that is, no removal was made of the last metal to freeze. There was no analog of the cropping of an ingot. As a result of shrinkage voids distributed over the ID of the casting, the inside of the finished tube contained imperfections not permissible in aircraft tubing.

Quite the same condition was met in a similar effort to produce blanks for ball-bearing races by centrifugal casting of alloy 52100.[326] Such cast blanks were cold reduced with equal facility to the hot-rolled tubing ordinarily used, but, since the ID was not machined, flaws similar to those noted above appeared on the ID of the finished race, and the material was not acceptable.

In these particular cases, lack of suitable facilities for cleaning up the ID led to abandonment of the centrifugal casting method, though with such a cleaning-up operation there is reason to expect that the serviceable castings might have been produced.

All these experiences show that it is futile to expect perfect ID on centrifugally cast tubes when no one would expect to use an ingot without cropping off the piped top. The piping shrinkage that results from the volume change in going from the liquid to the solid has to take place. In the centrifugal casting it takes place all over the ID and the resulting unsound inner surface has to be removed from any such casting where a sound ID is needed, just as it is removed from centrifugally cast guns. In cases where such removal is done, as in centrifugally cast guns, centrifugally cast tubes are capable of giving high-quality metal.

An effort to produce a duplex metal casting of steel within copper, for the purpose of conserving copper in driving bands for shells, proved unsuccessful.[326] The steel solidifies first and undergoes its normal shrinkage while the surrounding copper is still molten along the interface. Centrifugal force then acts to separate the two metals rather than to bring them together. Duplex driving bands are discussed also in Chapter 5 of this report.

The progress reports cited in the foregoing give all details of the investigation while the final report[327] summarizes the work.

7.2.6 Commercial Application of the Process

Correlation Project NRC-61A, Experimental Production of Pilot Static and Centrifugal Castings for the Armed Services, which was financed and conducted by the American Brake Shoe Company under the general supervision of the War Metallurgy Committee, was a study of the application of the centrifugal casting process to the manufacture of composite grinding rolls.[328] In this investigation, techniques were developed, much operation data were obtained, and practices were recommended. Also studied under this project were the differences in the fluidity of various commercial grades of heat-resisting alloys. An improved method was developed for evaluating fluidity by the cast spiral technique.[329]

7.3 PRECISION CASTING

As a result of a number of informal suggestions from the Armed Services and the War Production Board as to the need for a general and rather elementary review of the field of precision casting of metals, the War Metallurgy Committee carried out Survey Project SP-14, Centrifugal and Precision Casting of Nonferrous Alloys. The report on this project[330] described the various methods of casting metals, and was intended for those having little or no experience in the field of precision casting, who might be urged to consider the production of such castings to ease the demand on forging and machining facilities. The portions of this report relating specifically to the so-called lost wax precision casting process were duplicated by OPRD and widely distributed to industrial concerns.

The above-described survey indicated the desirability of further study of precision casting methods so that they could be applied to the production of war matériel, such as intricate parts for artillery and small arms firing mechanisms, parts for breech mechanisms, rocket nozzles, and other urgently needed parts made from commercial structural steels ur-

gently needed, but the production of which was hampered by the lack of machine tool capacity and the need for an excessive amount of hand work. The precision casting process also held promise for the production of alloy metal parts from materials not forgeable or machinable. Project NRC-69, Development and Extension of Precision Casting Methods for Production of Miscellaneous War Matériel Items, was established in the research laboratories of the General Electric Company because that company was one of the pioneers in the field of precision casting. Subsequently, the Army Ordnance Department assumed the sponsorship of the project under control number OD-144.

Dentists and jewelers have long been accustomed to making small castings of precious metals to very precise dimensions. A model is made in wax, coated with a wash that will give a smooth surface on the final casting, and "invested" in a refractory material. The wax is melted out, and the metal cast into the space formerly occupied by the wax. This is the so-called lost wax process which had been used by the ancient Greeks in making statuary.

The dentist uses this method not because his alloys could not be formed in other ways, but merely because it is the simplest way of making just one object of particular dimensions and contour. However, the process also serves for production of repetition castings, very close to size, of alloys that cannot be forged or machined, and which would be difficult to cast to required dimensional tolerance by more common foundry methods. It will produce, with even better dimensional certainty than die casting, castings from alloys of such high melting point that they cannot be die cast. It has been especially valuable in the production of supercharger buckets from special heat-resisting alloys, difficult or impossible to forge or machine.

In production of such parts by the millions, instead of modeling the wax pattern for each casting as is done when only one casting is to be inside, many wax patterns, exact duplicates of each other, have to be prepared. Hence, a master pattern is constructed and from this a mold of soft, low-melting alloy is made. Into this mold is forced a suitable wax, using injection molding methods, such as are employed in molding plastics.

One or more of the wax patterns so made, coated with a fine-grained precoat, are surrounded with a suitable refractory slurry, which sets up to a hard mass. The wax is then melted out, the mold suitably preheated, and the metal to be cast poured into the mold, sometimes being forced in by air pressure, sometimes centrifugally as in common dental practice.

While these steps sound simple, it should be noted that (1) the wax pattern is warm and expanded when formed, but cold when surrounded with investment, and (2) the refractory mold expands when heated, and the final casting contracts on cooling. All these thermal dimensional changes have to be allowed for, each material used in the sequence of operations must be suitably chosen, and the gating of the wax pattern must be so designed that the wax will melt out cleanly and the casting be properly fed so as to be sound. Thus, many important steps have to be worked out for each particular case. Once they are worked out, castings can be produced with marvelous precision of dimensions, often requiring no finishing other than removing gates, and perhaps buffing.

Obviously, the difficulties increase as the size of the piece increases. Small turbine blades of alloys difficult to form by other methods and several small gun parts of ordinary steels requiring very close dimensions and costly machining account for much of the production. Under either of these conditions the process is economical, although it would seldom be economical for parts easily made by other processes or not requiring extreme closeness of dimensions. Somewhat analogous methods, using plaster molds, are used for certain brass or aluminum castings, in which high, but not extreme, dimensional precision is required.

Each object to be made by precision casting is a problem in itself and has to be studied as such. Part I of the final report on the project[331] describes in rather general terms the fundamentals of the process and the various steps used in precision casting, particularly in the casting of ferrous and higher melting nonferrous alloys. Some of the parts made were cast rocket jets, cast gun parts, and escort vessel turbine valves. The General Electric Company also instructed personnel of several commercial concerns and governmental agencies in the art of making precision castings. Part II of the final report[332] briefly describes the achievements of the organizations that were instructed in precision casting methods through the activities of the project. The experience of Watervliet Arsenal in making precision-cast gun parts is reviewed and the cost data indicative of the savings affected through the use of the process are

given. It is noteworthy that the precision-cast gun parts not only had properties equal or superior to those manufactured by conventional machining or forging operations, but also were manufactured at a considerably lower cost. For example, a trigger of SAE 3415 steel costs $8.33 when made by machining methods and but $1.69 when made by precision casting methods and finished. Other comparisons were less striking, but in all examples cited the saving amounted to more than 30 per cent.

Part II of the final report[333] on Project NRC-61A, Experimental Production of Pilot Static and Centrifugal Castings for the Armed Services, gives a realistic and detailed account of the difficulties met, of how some were overcome, and of the logical steps for overcoming the others, in making gas turbine diaphragms by a modification of the precision casting method. This report gives considerable insight into the process and is commended to those who are concerned with the production of large, heavy, and intricate castings.

7.4 REFRACTORIES

Investigation of two refractory problems was undertaken by the former Division B, NDRC, at the request of Watertown Arsenal. These problems involved the development of a substitute for sillimanite and studies of pouring box refractories. The projects were established prior to the outbreak of World War II and their supervision was transferred from Division B, NDRC, to the Metallurgical Advisory Committee of the National Research Council (later the War Metallurgy Committee) in March 1942. The work was completed shortly thereafter.

7.4.1 Substitute for Sillimanite

Project B-95 (OD-35-2), Development of Substitute for Sillimanite in Pouring Rings Used in Special Steel Foundry Practice, was conducted by the Massachusetts Institute of Technology. The objective of the investigation was to develop a substitute for sillimanite, or Indian kyanite, because of their scarcity due to unsettled world conditions. It was found that a kaolin grog-clay-sodium silicate mixture, all domestic materials, was a suitable substitute refractory for pouring rings, although there was no assurance that the mixture would be suitable for other refractory purposes. The mixture was proved satisfactory in ramming and casting operations at Watertown Arsenal.[334,335] In addition to this development, a mold was designed for the mechanical pressing of the pouring rings. Trials made using this method indicated that a large amount of time and labor could be saved in molding as well as accomplishing considerable improvement in the quality of the finished pouring rings.[335]

7.4.2 Pouring Box Refractories

Project B-103 (OD-35-1), Acceptance Test for Firebrick: Pouring Box Refractories, was carried out by Ohio State University. The objective of this investigation was to develop a rapid acceptance test method for fire clay brick to be used at Watertown Arsenal in pouring boxes for handling molten steel where the brick must endure high thermal shock. Under the project a simple slag penetration test was developed. This involved studies of the properties of the refractories used, the design, construction, and operation of a slag test furnace, and the correlation of the test results with the experience of Watertown Arsenal in the behavior of the various refractories used. The work was done with the active cooperation of Watertown Arsenal and sufficient data were obtained for the preparation of specifications for pouring box refractories.[336,337]

Chapter 8

EXAMINATION OF ENEMY MATÉRIEL

THE RESEARCH and development program of the Armed Services required an intimate knowledge of enemy matériel. Early in World War II the War and Navy Departments organized specialized groups to study captured equipment in the field and to secure representative samples for more complete examination in this country. Collection centers were established at Aberdeen Proving Ground by the Office of the Chief of Ordnance, War Department, and later at Anacostia by the Office of the Chief of Naval Operations, Navy Department. Equipment was tested functionally at these centers or sent to the service laboratories or the arsenals for more complete examination.

After functional tests were completed, it was frequently desired to know more about the materials and manufacturing methods used by the enemy than could be secured conveniently by the service laboratories. It was recognized that civilian research laboratories and civilian metallurgists, chemists, and engineers who had broad familiarity with production methods could be used to advantage to supplement the service organizations in securing the detailed information needed to establish trends in development projects and in the use of materials.

This type of information was also needed by the Board of Economic Warfare to follow the economic aspects of the changing materials situations in the enemy countries.

Accordingly, after consultation with the Army Ordnance Department, the Board of Economic Warfare (later the Foreign Economic Administration), members of the War Metallurgy Committee, and investigators of the Division 18 projects on armor plate, gun steels, and other materials of war, it was recommended that a project be established for the examination of enemy matériel as part of the research program of Division 18.

The project was established at Battelle Memorial Institute as Project NRC-32 in September 1942. Subsequently, the Army Ordnance Department, the Army Air Forces, and the Navy Department endorsed the project through channels assigning their control numbers OD-113, AC-77, and N-119, respectively. A project committee was appointed by the War Metallurgy Committee to advise in the selection and examination of matériel.

Items of captured matériel were selected by the project committee to provide information for Division 18 NDRC research projects as well as the War and Navy Departments, the Foreign Economic Administration, and the Office of Strategic Services. Most of the selections were made after consultation with the interested branch of the Armed Services, while some of the items were selected by the Services and shipped to Battelle Memorial Institute for examination.

The project was organized to use the specialized knowledge and facilities of the various laboratories and industries anywhere in this country as might be indicated by the particular item under study.[a]

The purposes of the project were, first, to find whether the enemies had improved compositions or fabrication practices and second, to note the progress of the conservation measures they adopted to combat raw material shortages.

The work dovetailed into that of the Armed Services and of the British. At the beginning it was chiefly on German projectiles and small arms without much attention to German aircraft, since the British were reporting on that. Later, some large German guns were studied. As Japanese matériel became available, the proportion of specimens of Japanese origin sent in by the Services increased. Japanese airframes and aircraft engines came in in considerable numbers. Aircraft instruments from both Japanese and German planes were also supplied. Periodic trips were made to collection centers to select informative specimens. When possible, selections of matériel for examination were made of chronological series of items to show changes indi-

[a] Organizations working on this project included:
Aluminum Company of America, Bendix Aviation Corporation Scintilla Division, Bendix Aviation Corporation Eclipse Aviation Division, Bethlehem Steel Corporation, Chrysler Corporation, Ethyl Corporation, Forest Products Laboratory, General Motors Corporation, Goodyear Tire and Rubber Company, Indiana Steel Products Company, The Massachusetts Institute of Technology, Mellon Institute, National Cash Register Company, The New Jersey Zinc Company, V. L. Smithers Laboratories, A. O. Smith Corporation, John A. Roebling Sons Company, Rome Cable Corporation, Wallace Barnes Company, Western Cartridge Company, and Wyman Gordon Company.

cating material shortages as well as possible trends in development.

The Services first examined the available matériel for its functioning and behavior before turning it over for study of material and fabrication, unless plenty of duplicates were available. Some articles of prime and immediate interest were at once examined as to material by the Services. The role of this project was to supplement such examinations and fill in gaps, so that a chronological history of enemy materials and fabrication practices might be built up, insofar as matériel of known dates of manufacture were at hand.

It was not expected that much of a startling nature or many striking innovations would turn up, for metallurgical practice is necessarily pretty much alike the world over, but it was considered necessary to watch for any such cases that might occur. Few cases were met where the enemy appeared to have anything different and worth copying. These were promptly followed up by the Services.

On the whole, the picture showed adoption by the Germans of chromium and manganese steels for heat-treated parts of heavy sections for vital service, with every possible economy in use of nickel. This development reflected the German supply problem and underlined the correctness of the program of strategic bombing and diplomatic and economic action to pinch off the supplies of chromium and manganese. The German shortage of copper also was very apparent.

As the war went on, the German products showed somewhat increased use of free-machining steels and labor-saving practices, though assemblies that would here be made from stampings by copper brazing or welding were still made by more laborious methods, and the application of free-machining steels was still astonishingly small.

German foundry practice, on both steel and aluminum alloys, was evidenced to be excellent. Machine work as to tolerances and finish was uniformly good. In general, the German implements of warfare were made from available materials so chosen and so processed that the implements were effective for their purposes. German technology produced reliable planes, guns, projectiles, and armor. Where their practice deviated from ours, it was usually with a purpose. Their armor welding was poor by our standards, but their tank design did not depend so much on the integrity of the weld as does ours.

They made more consistent use of steel cartridge cases than we, being forced to this by the copper shortage. Their use of porous iron driving bands, probably motivated at first by the copper shortage, was probably accelerated by an even more satisfactory performance of the bands than they expected.

These bands are very brittle by ordinary tests but do not act brittle under the stresses imposed on them in service. The porous iron band deserves more attention than it has had here, especially from the point of view of duplicating the porosity and not trying to make a band of the greatest possible solidity. The Germans used some solid, soft iron bands but soon found the porous band preferable.

The Japanese products showed little variance from the old, established prewar choices of materials. Probably because of the availability of Chinese tungsten, some of their heat-treated steels utilized tungsten as an alloying element, but in general their choice of materials reflected German practice of about 1930 and even went beyond it in lavish use of nickel.

In some cases the materials and processing were exact duplicates of those used in German or American products which they were copying as to design.

The raw materials classed as strategic or critical in the United States and even more in Germany were used by the Japanese without stint, so lavishly as to suggest that huge stock piles of raw materials and alloying elements, especially copper and nickel, had been accumulated and were being drawn upon without thought of conservation. In a few instances of late 1943 or 1944 manufacture, aircraft engine parts, previously high in nickel, were of low nickel or nickel-free steels with chromium and manganese as alloys, but this may as well have been the copying of late German practice as motivated by conservation requirements.

Rarely was metallurgical initiative shown, though the use of the strong aluminum-magnesium-zinc alloys in fighter planes was an innovation adopted on their own initiative.

Japanese products were often made with a vast deal of handwork and by roundabout methods, not because they did not know better methods, since some parts are made in up-to-date fashion, but evidently for lack of processing equipment for rapid, large-scale production. Despite this, the workmanship, though seldom up to the German standard, is fair and generally adequate for the purpose in hand.

Some very poor ball bearings of Japanese make were found, made of the conventional steels but sloppily heat treated, probably because of poor equipment and inadequate inspection.

On the whole, however, the Japanese implements of warfare were of good, usable quality. The Japanese bottleneck was more probably in iron for tonnage steel rather than in alloying elements. The tonnage steel, and even most of the alloy steels, carry residual elements, indicating wide use of scrap metal that would ordinarily be considered inferior, and undoubtedly much of the second grade scrap that was sold to Japan during the appeasement period entered into implements of warfare for use against us.

Neither the Germans nor the Japanese went far toward conservation of steel alloying elements by considered use of the content of such elements found in scrap as we did in the National Emergency steels.

The German scrap situation did not lend itself to such a solution as well as does American scrap. Japanese scrap could have been somewhat more readily adapted. In only one case, that of a torsion bar for a Panzer tank, was boron used to enhance hardenability, and that was late in the war.

This project, which covered the examination of 794 individual samples or shipments of diverse nature, has been reported in 215 topical reports,[338-553] not many of which are interconnected. A list of the titles of these reports as well as a subject index of the items examined are given in the final report[554] on the project and should be inspected when details are sought.

A general summary of the earlier examinations, correlated with published British reports, was published.[555] These examinations related chiefly to guns, ammunition, and aircraft, and give a picture of German and Japanese war metallurgy very similar to that reported from a study of automotive equipment.[556]

Another project dealing with enemy materials rather than matériel was Survey Project SP-6, Abstract of a Confidential Report on Nickel in Japan. This project was carried out by the War Metallurgy Committee as a result of a request directed to NDRC by the Far Eastern Branch, Military Intelligence Division G-2, War Department General Staff in April 1942. Under this project a voluminous document was abstracted.[557] Although the document contained no useful information on new alloys or substitutes for nickel steels, it did yield information as to possible bombing objectives to bottleneck Japanese production of nickel.

Chapter 9

MISCELLANEOUS MATERIALS FOR WAR

9.1 INTRODUCTION

UNDER the classification of miscellaneous materials for war are grouped a number of investigations relating to studies of materials used in miscellaneous instrumentalities of warfare that were not integral parts of the programs described in the foregoing chapters. Although some of these investigations are mentioned in other sections of this summary in instances where phases of the work had direct bearing on the program of that section, the references there cited covered only the phases of the program being discussed.

9.2 MATERIALS FOR QUARTERMASTER'S SUPPLIES

Several problems were presented by the Office of the Quartermaster General for study by NDRC. These comprised the development of fused inorganic coatings for cooking utensils, investigations of plated steel flatware for military use, general metallurgical studies of quartermaster's supplies including methods of camouflaging mess gear, and the evaluation of the corrosion-resisting properties of an alloy that had been suggested for use in quartermaster's items.

9.2.1 Fused Coatings for Cooking Utensils and Other Quartermaster's Supplies

Project NRC-46 (QMC-18), Development of a Suitable and Noncritical Fused Inorganic Coating for Cooking Utensils and Other Quartermaster's Items, was established in the laboratories of the Ferro Enamel Corporation. The program originally formulated comprised investigations which might lead to the development of fused inorganic coatings for steel canteens and cooking utensils, studies of the possible use of combinations of fused inorganic coatings and metallic coatings for the edges and corners of the articles, and the gathering of data from which recommendations could be drawn for establishing satisfactory specifications. The Quartermaster Corps desired, as quickly as possible, coatings that would be capable of withstanding rough usage and would be nonreflective, nontoxic, and adaptable to camouflage.

Before the project was completed, the metal supply situation changed and stainless steel and later aluminum became available for canteens. As a result, the aim of the project was changed and the work was concentrated on the development of coatings for such quartermaster's articles as spark arresters, tent hardware, stoves, stovepipes, and cooking utensils. Not only were a number of coatings developed, but also trials were made of commercially available coatings.[558]

Two developments made under the project are noteworthy, and it is understood that, in part at least, they have been adopted by the Office of the Quartermaster General. One is a cemented inorganic coating applied at low temperatures (under 500 F). The other comprises applying a so-called slag coating and then over it a thin matte finish of vitreous enamel. This coating combines corrosion and erosion resistance, and, as it has a matte finish, glare is absent. In addition, objects can be finished in olive drab or camouflage colors. Samples of the more promising coatings were supplied to the Army and Navy liaison representatives for the project as well as to the Conservation Division, War Production Board. The Military Planning Division of the Office of the Quartermaster General sent a set of these samples to the National Bureau of Standards for evaluation. Information as to the results of these tests and the extent of the adoption of the coatings developed is not available.

9.2.2 Flatware for Army Use

In 1941, the necessity for diverting copper, nickel, zinc, and chromium to the most essential military uses led to the substitution of plain carbon steel for nickel-silver and stainless steel in flatware procurement by the Armed Services. The specifications issued at that time, RR-T-56, provided for plating or coating steel with tin, nickel, chromium, or silver according to accepted commercial practice, with the usual undercoatings of different metals. Subsequently, an

emergency specification, E-RR-T-56, was issued limiting approved coatings to silver directly on steel. It soon became clear that flatware made by plating silver on steel was not of the anticipated quality. Although early difficulties from peeling and blistering of the coatings were overcome, the susceptibility of the ware to staining by rust was seriously objectionable. In 1942, the Conservation Branch, Production Division, Headquarters, Services of Supply, War Department, requested the War Metallurgy Committee to make a study of plating silver directly on steel. A committee was appointed and Survey Project SP-11, Silver Plating of Steel Flatware, was established. The committee consulted with flatware manufacturers as well as with representatives from the Armed Services and the War Production Board. A comprehensive report on the situation was issued[559] and, as there was no known method for fabricating silver-plated steel flatware that would not eventually rust in service comparable to that required by the Armed Forces, a research program was recommended. As the result of this report, the Office of the Quartermaster General requested that NDRC undertake investigations under the control number QMC-21. Project NRC-48, Flatware for Army Use, was established at the Reed and Barton Corporation for the purpose of having flatware made by various procedures for service testing. The contract for the manufacture of this flatware was virtually a procurement contract and the committee for Survey Project SP-11 provided the procedures, drew up a test program, and evaluated the results. This committee included liaison with the Army and Navy, the War Production Board, and the National Bureau of Standards, thus knitting together the several investigations being carried out on the subject. The objective of this project was to investigate the use of the less strategic metals, for example, silver alloys, other metals and alloys, and composite coatings for the protection of steel flatware from rusting in service, and to coordinate tests and data from the several government agencies interested in the subject.

Lots of approximately 500 pieces of each of thirty-five types of mild steel forks plated with electrodeposited coatings of silver, chromium, and composite coatings of these metals with copper and nickel were prepared under the supervision of a member of the committee. Samples of each type were examined by the National Bureau of Standards and a number of pieces from each lot were subjected to test in the mess halls of Camp Lee, Virginia. These tests were conducted by the Quartermaster Board and were examined weekly by observers. The unserviceable forks were withdrawn from the test and returned to the chairman of the committee.

Part I of the final report[560] on Survey Project SP-11 (QMC-21) gives the results of one full year of field service tests. Part II[561] covers the results of the service tests beyond 368 days to a total of 599 days. Appended to this report are reports from the National Bureau of Standards, and the Quartermaster Board on the parts they played in this cooperative effort. A report of the U. S. Naval Engineering Experiment Station also is appended to bring together all the significant reports on the testing of flatware for military use.

As a result of this investigation, the committee made recommendations as a guide in the preparation of specifications and in the supervision of the manufacture of plated steel flatware for military mess hall use.

9.2.3 General Metallurgical Studies

In February 1943, the Research and Development Branch, Military Planning Division, Office of the Quartermaster General, requested the War Metallurgy Committee to initiate a project to deal with miscellaneous metallurgical problems relating to quartermaster's supplies. As a result of this request, Project NRC-54, Metallurgical Studies and Surveys of Army Quartermaster Corps Supplies, was established at the Massachusetts Institute of Technology. Work on this project did not involve extended research programs but consisted of the study of many isolated problems, some of which required incidental experimental work for their solution. These problems changed constantly because of the changing needs of the Armed Forces and also because of the constantly changing availability of certain metals which had been found satisfactory but for which substitution had to be made in the emergency. The investigator worked closely with the Office of the Quartermaster General and in particular with the Boston Quartermaster Depot.

The final report on the project[562] is topical and fragmentary as in most instances the urgency of the need made it impossible to follow through to a wholly satisfactory conclusion. Generally speaking,

the problems were concerned with metals used in any form of quartermaster's supplies from shoe eyelets to gasoline containers. Experimental work and consultations covered mountain and ice equipment such as ski binders; rock pitons, and ice pitons; cooking and messing equipment; and miscellaneous items such as small tools, shoe eyelets and hooks, toe and heel plates, pails, and refuse cans.

9.2.4 Camouflage of Mess Gear

Another phase of the foregoing investigation was the study of the camouflage of mess gear (QMC-25). In the Southwest Pacific Theater, there was a need for a surface which would be nonreflecting and at the same time would withstand severe shock and exposure to high temperatures, even to flame temperatures. A series of experiments led to the preparation of a number of canteens coated by a metal spray process. These canteens had a dull surface and various colors could be produced by variations in the metal powder compositions.[562] As far as could be determined by rough tests, these coatings were satisfactory. Their resistance to impact, abrasion, and heat, as well as their toxicity, was determined by the National Bureau of Standards. Information as to the results of these tests and the extent of the adoption of the process, if adopted at all, is not available.

9.2.5 Evaluation of the Corrosion Resistance of a Special Alloy Steel

At the request of the Office of the Quartermaster General, Project NRC-91 (QMC-39), Development and Evaluation of an Economical Corrosion Resisting Alloy for Quartermaster Items, was established at Battelle Memorial Institute. The objective of this project was to evaluate the corrosion resistance of Alcuphos, a special alloy steel developed at the Jeffersonville Depot, to determine its suitability for possible use in flatware. It was believed that this alloy had corrosion-resisting properties which would be of value in tropical areas. The corrosion tests performed on Alcuphos with mild steel, stainless steel, and an aluminum alloy for comparison, comprised tropical humidity tests, salt-spray tests, industrial atmosphere tests, and spot tests with selected foods. These tests demonstrated, in every case, the susceptibility of Alcuphos to corrosive attack. In some cases, the test suggested that Alcuphos is less resistant than mild steel. Both stainless steel and the aluminum alloy showed excellent resistance to the several corrosive environments.[563] Therefore, the project was abandoned.

9.3 PROPERTIES OF MISCELLANEOUS MATERIALS

9.3.1 Low-Temperature Properties of Metals

In August 1940, the Office of the Quartermaster General requested NDRC to study the physical changes occurring in metals and other materials under extreme cold conditions as these changes precluded the simple adaptation of conventional designs and materials used in standard production motor vehicles. This information was desired in the development of motorized transport equipment for Army use in arctic climates. Action on establishing a project was delayed until the problem could be discussed with Watertown Arsenal. As a result of this conference, the Metallurgy Section of the former Division B of NDRC recommended that a thorough study of all available data be made before the formulation of a definite research program. In March 1941, Project B-89, Literature Survey on the Low-Temperature Properties of Metals, was established at the University of Michigan by the former Division B of NDRC. The final report on this project comprises seven volumes and covers the information available at that time on the low-temperature properties of metals and alloys, both ferrous and nonferrous. Each major group is divided into subgroups, according to alloy types.[564]

The effect of low temperatures on the cleavage fracture of ship plate is discussed in Chapter 6 of this summary report. It is noteworthy also that studies of the behavior of ferritic steels at low temperatures were the subject of an investigation carried out for the Office of Production Research and Development of WPB under the supervision of the War Metallurgy Committee.[3]

9.3.2 Behavior of Metals under Dynamic Conditions

Prior to 1942, the study of the behavior of metals under dynamic conditions was concerned princi-

pally with the assembly of data from notched bar impact tests. There had been some activity toward obtaining information on the performance of metals in tension impact. In spite of the abundance of data, there was not a clear fundamental understanding of the conditions involved in impact loading except in the case of elastic behavior. It was well recognized that elastic strains were propagated in bars with the velocity of sound, but when plastic strain was involved the behavior of the bar could not be interpreted. If materials were to be subjected to impact loading and tested in that manner to destruction, it was necessary to be able to interpret the results in a manner that would have significance in practical applications.

For some time engineers have believed that many machine parts and structures are subject to impact loading, and, furthermore, they have observed that the performance of some materials when subjected to dynamic loading is different from that experienced under static conditions. To explain these differences, a fundamental concept must be established. By the development of this fundamental concept, it was hoped that a basic understanding of the dynamic performance of metals not only under impact, but also under high strain rate and rapid loading conditions, could be obtained.

In March 1942, the former Division A of NDRC established a project at California Institute of Technology to undertake experimental and theoretical investigations, for various high rates of strain, of the propagation of plastic deformation in wires, bars, and beams under conditions in which end effects could be neglected. It was believed that the theory proposed by von Kármán[565] and partially confirmed in earlier work under Division A,[566] would be useful in connection with the understanding of the mechanism of projectile impact and penetration. Work on this problem was informally requested of Division A by the Naval Proving Ground and endorsed by the NDRC ad hoc Armor Committee.[78] It was requested also by the Bureau of Ordnance, Navy Department, under their control number of NO-11. Subsequently, the Bureau of Ships, Navy Department, requested, under their control number NS-109, work relating to the behavior of ship building materials at high rates of loading to provide basic data for use in the design of structures subjected to shock loading. The project was of interest also to the Corps of Engineers under their control numbers CE-5 and CE-6.

With the reorganization of NDRC, the supervision of the project was transferred from the former Division A to Division 2. In January 1944 the project was transferred from Division 2 to Division 18 and continued as Project NRC-82 (NS-109), Behavior of Metals under Dynamic Conditions. At that time, the program was revised to emphasize topics which held promise of being of most immediate value to the war effort. These comprised studies of impact loading on aircraft materials, gun steels, and ship plate.

According to the von Kármán theory of the propagation of plastic deformation in solids, the velocity of propagation of a plastic strain is less than that of an elastic strain; the velocity of propagation of this plastic strain decreases with increasing strain when the slope of the stress-strain diagrams decreases continuously; and plastic strain will increase with increasing velocity. When this theory is applied to the case of a long prismatic bar put suddenly into motion with a constant velocity, if the impact velocity is sufficient to produce a strain corresponding to the ultimate strength of the material in the bar, necking or rupture will occur at the moving end of the bar without causing very large plastic deformation further along the bar. The impact at which this occurs is termed the critical velocity.

The principles of this theory were verified in a preliminary manner by Duwez[566] from impact tests with long wires. Later tests with short specimens verified the existence of a critical velocity.[567] The computation of the critical velocity is based upon the static stress-strain diagram. The agreement between the experimental and computed critical velocity is not too close in all cases. However, data has been presented in these investigations to show that the dynamic stress-strain diagram is higher in some materials than the static diagram.

Further theoretical work[568] was carried on to take into account the reflection of plastic strain waves at the end of a bar of finite length. The effect of release of the impact load on the performance of bars has been considered. A graphical method of analysis was developed which is carried through in a more extensive manner in a general report.[569] These methods of analysis make it possible to establish the stress-time relations in a member subjected to tensile impact.

It has been found that the simple theory of plastic strain propagation cannot be applied to materials for which the stress-strain diagram shows a yield

point. In the interest of this problem a preliminary study was made of the mechanism of the progression of plastic yielding.[570] While the results of this study did not provide a means of taking care of yielding in the strain propagation theory, it gave some significant information. It appears that in the usual static tensile test, yielding progresses in jumps and the strain associated with these jumps is the strain corresponding to the end of yield on the static stress-strain diagram. Actually the strain at yield, whether static or dynamic, is not less than the strain at the end of yield when considered over a small increment of the gage length.

It is natural to question the validity of the theory of plastic strain propagation for compression loading. An investigation[571] was made, and it was found that the theory holds whenever the compression stress-strain diagram is concave downward. Tests were made with steel and lead. With the latter material it was shown that the concept of a critical velocity holds for the case of compression. The critical velocity for the steel is greater than the impact velocity attainable with equipment at hand.

Although the experimental work has shown certain discrepancies with respect to theory, it is to be remembered that the theory is based upon ideal conditions involving perfect impact by a rigid body. Also, the theoretical computations are based upon the static stress-strain diagram. The experimental work has given definite evidence to the effect that the stress-strain diagram under dynamic conditions is higher than under static conditions.

Influence of Impact Velocity on Tensile Properties

While the tensile impact tests on long wires were directed toward verification of the theory of the propagation of plastic strain, tests were made on specimens with a gage length of 8 in. These specimens were carried to failure and the force-time relations were determined. This provided data on the influence of impact velocity on the ultimate strength, percentage of elongation, percentage of reduction of area, and energy required to rupture. More extensive tests on long wires were made followed by tests on 8-in. specimens in the first part of these investigations.[567] While the tests on the short specimens provided information on specific metals, they also proved the existence of a critical velocity.

Some tests[572] were directed toward a comparison between the experimental and theoretical strain distribution curves. The method of computing the reflection and stopping of plastic waves was shown to be substantially correct.

One may well be concerned with the effect of the dimensions on the results of impact tests. Such an investigation was made.[573,574] In one series of experiments an investigation was made of the behavior of long specimens of a material which exhibits yielding where it was shown that the velocity of propagation is a multivalued function and the strain distribution differs from that computed by the theory. It was also shown that such a material can sustain a stress approximately three times the static yield point without the occurrence of plastic strain, provided the duration of the application of load is short. Other tests were made to determine the influence of gage length on the results of tensile impact tests. It was found that the critical velocity was not affected by the gage length. However, the gage length must be less than 4 in. to show the critical velocity clearly.

Another investigation[575] was made to study the influence of general specimen dimensions and shape on the results of the tensile impact tests. From these tests it was apparent that if the ratio of length to diameter was greater than 13, the results were not altered. Furthermore, the shape of the specimen within the range considered had no effect on the test results. The accuracy of tensile impact test results has been studied in some detail.[576] The experimental error in so far as energy measurements are concerned is not more than plus or minus 10 per cent.

Tests were made on a rather large number of ferrous and nonferrous metals and alloys in the determination of the influence of impact velocity upon the tensile properties of these materials. Investigations were made over a range of impact velocities up to 200 fps. The details of these tests are covered in individual reports.[577,584] A general summary of these data is presented in a separate report.[585] As a result of these investigations taken with the theoretical analysis, it was shown that only the force-time or stress-time diagrams can be obtained in tensile impact tests and that these diagrams cannot be transformed into stress-strain diagrams. The conclusion is that in tensile impact tests the results cannot be logically referred to values of strain rate. Inability to transform these diagrams is due to propagation effects which give rise to a nonuniform strain rate over the gage length of the specimen.

Tests made so far indicate that the dynamic tensile properties of materials cannot be predicted from their static properties, although the order of magnitude of the critical velocity may be predicted with reasonable reliability on the basis of the static stress-strain diagram. It has been found that the ultimate strength of all materials tested so far is never less than the static value at impact velocities in the range of 25 to 200 fps. In plotting the percentage of elongation against impact velocity, the data appear to follow one of three types of relations:

1. Elongation is constant (either higher or lower than the static values) within a certain velocity range followed by a decrease in elongation at higher velocities.
2. The elongation increases uniformly to a maximum and then decreases with continued increase in impact velocity.
3. The elongation values are scattered with a tendency to increase with increasing impact velocity and then to decrease slightly above a critical impact velocity.

The influence of impact velocity on the energy required to rupture the specimen follows the same general tendency as the percentage of elongation for the materials tested in these investigations. It was concluded that, in general, the higher the static ultimate strength and percentage of elongation, the lower is the percentage of increase of strength and elongation under dynamic conditions.

Some of the work included a study of the influence of heat treatment on the tensile impact properties of several steels.[579,580,583,586] In some it was found that, in a steel heat treated to hardnesses of the order of 50 Rockwell C, better dynamic properties were obtained by austempering than by quenching and tempering. On the other hand, when these same steels were heat treated to a hardness of about 30 Rockwell C, quenching and tempering appeared to give better dynamic properties. To carry this line of investigation further, other tests[586] were made specifically on an SAE 4340 steel which was heat treated by three procedures, namely, quenching and tempering, martempering, and austempering. The range of hardness covered was from approximately 28 to 49 Rockwell C. All these tests were made at an impact velocity of about 100 fps. For hardnesses in the range of about 48 Rockwell C, it was observed that an austemper or a martemper treatment gives a slightly higher value of energy required to rupture than a quench and temper treatment. For hardnesses in the lower range, a quench and temper or a martemper treatment gives slightly better energy values than an austemper treatment. These results might be helpful in certain applications in the selection of the proper heat treatment and hardness range for certain specific requirements where it is recognized that impact conditions prevail. However, it must be remembered that the austempered specimens tested were of very small sections and that austempering is not in general applicable to large sections.

Compression Impact

In the discussion of the development of the theoretical aspects of plastic strain propagation, it was stated that the relations established by von Kármán are believed to hold in the case of compression impact for materials in which the static stress-strain diagram was concave downward.

A series of tests was made on annealed copper, cold-drawn copper, annealed SAE 1020 steel, cold-drawn SAE 1020 steel, a zinc base alloy die-casting, and lead. It has been shown[571] that the theory of strain propagation is valid in compression for strains which are less than those corresponding to the inflection in the static compression stress-strain curve. Reasonably good evidence had been presented to show the compressive elastic limit of annealed SAE 1020 steel under dynamic conditions to be about 40 per cent greater than the static value. The experiments with lead have given evidence of the existence of a critical velocity of about 100 fps in compression. At impact velocities greater than this value, plastic strains greater than approximately 35 per cent could not be detected in the specimens tested. It appears that the velocity of plastic deformation in lead for strains greater than 35 per cent is too low to permit longitudinal displacement of material and, therefore, the material is displaced laterally. In view of these results the critical velocity of annealed copper, cold-drawn copper, cold-drawn SAE 1020 steel, and class B armor plate were computed to be 1,050, 1,220, 1,440, and 1,750 fps respectively. It is to be noted that these critical velocities are considerably above those which are found in the case of tension. The principal of strain propagation in compression was also considered for a practical problem.

The results of the compression impact studies led to a consideration of the mechanism of penetration of plates by projectiles from the standpoint of strain

propagation.[587] Some tests have been made in which a projectile 0.224 in. in diameter was fired at copper disks of different thicknesses at a velocity of about 3,900 fps. In plotting the square of the residual velocity against the thicknesses of the disks, a definite discontinuity was observed. It is believed that this discontinuity is related to the change of velocity of the projectile during penetration. This discontinuity in the curve has been interpreted on the basis of the theory of strain propagation. These tests were of exploratory character and were not carried further.

Impact on Beams

In view of the success attained in the application of the theory of plastic strain propagation to longitudinal impact, both experimental and theoretical investigations were made on the behavior of beams under conditions of impact loading. The investigations included tests on small rectangular freely supported beams 10 ft long and a theoretical analysis of infinitely long beams.[588] The materials included cold-rolled and hot-rolled low-carbon steel and annealed copper. Deflection curves at the end of impact and after the beams returned to rest were obtained. A theory was developed for the plastic deformation of an infinitely long beam subjected to a concentrated transverse impact of constant velocity. The results show that for a material such as low-carbon steel, for which plastic deformation is localized, the observed deflection curve is closely approximated by considering the elastic behavior in the theoretical case. Two approximations of the moment-curvature curve have been given by which the deflection characteristics may be computed for certain cases.

With the development of the theory of propagation of plastic bending and its verification, experiments were made on beams for which the ratio of depth to length and the mode of clamping and loading was somewhat closer to those which might be experienced in practice.[589] The impact load was obtained by means of a mass moving with a certain velocity. The total kinetic energy of the hammer was absorbed by the beam. Consequently, the impact velocity after initial impact was not constant, as in the test utilized to confirm the theory, but decreased progressively to zero. An I beam and a rectangular beam of the same section modulus, 40 in. long and clamped at the end, were investigated. These beams were of extruded sections of 24S-T aluminum alloy. In general, the results showed that the center deflection of the beam increases approximately linearly with the kinetic energy of the hammer. It appears that, for a given type of beam and a given amount of kinetic energy of the hammer, the damage as measured by the center deflection is greater for a heavy hammer with a low impact velocity than for a light hammer with a high impact velocity. Furthermore, it was shown that a beam with a greater cross-sectional area evidences less damage than another beam of the same section modulus.

Records were made of the force on the beam at the point of impact as a function of time. These determinations show that the force reaches a maximum value rapidly and then decreases progressively. If two beams having the same section modulus but different weight per unit length are subjected to the same conditions of the impact, the force acting on the hammer will be greater for the heavy hammer.

Impact on Plates

Interest in the perforation of plates by projectiles led to a consideration of the application of the theory of strain propagation to the action of a punch at the center of a plate under conditions of impact loading. For this purpose a preliminary investigation was made.[590] In this work the impact velocities were less than 150 fps. Both hot-rolled and cold-rolled plates ¼ in. thick and 7¼ in. in diameter were employed. Three types of punches were used, namely, flat end, conical end with 75-degree included angle, and conical end with 45-degree included angle. These plates were clamped at the periphery. While these tests were of preliminary character, they showed that a certain velocity exists above which the maximum deflection in the plate decreases markedly. This velocity appears to be independent of the shape of the punch. Deflection curves are given for various velocities up to approximately 150 fps and for static loading.

In view of the results of the preliminary tests with plates, a theoretical study was made on the plastic bending of circular plates with both static and impact loading at the center.[591] A reasonably satisfactory agreement was obtained between theoretical and experimental static deflection curves. In general, it was found that the law of propagation of bending strain which had been found to hold for beams is also true for plates.

The small diameter of the plates used in the pre-

vious work did not permit as extensive conclusions as were desired. An investigation was made on steel plates ¼ in. thick, 6 ft and 3 ft in diameter, loaded in impact at the center with a spherical punch.[592] In these tests the plates were supported at the edge and stuck at the center at different impact velocities and for several durations of impact. Velocities ranged from about 55 to 205 fps, with the duration of impact between 0.4 and 2 msec. The deflection curves were determined at the end of impact and after the test was completed. The results indicate that the point along the diameter at which the deflection is zero travels from the center of the plate toward the support proportionally to the square root of the time. The relation is in agreement with the theory based on bending stress only and is not in agreement with the membrane theory also discussed in the report of this work. It appears from these results that a theory covering the dynamic deflection of a plate must include both tensile and bending stresses.

A series of tests was made on a Zamac II die-cast alloy for the purpose of investigating its dynamic properties for a specific application.[593] Tensile impact and static-bend tests were made at temperatures between −58 F and 70 F.

Strain Rate

In the investigation of longitudinal impact, the results were obtained with the aid of force-time curves determined during the impact tests. It is important to realize that these force-time diagrams cannot be transformed into stress-strain diagrams. This restriction is based upon an understanding of the theory of strain propagation. By applying the theory of strain propagation, it is possible to determine the rate of strain at any specific point along the specimen as a function of time. From these considerations, it was shown that the rate of strain varies widely from one point to another and that the strain rate at any point may differ markedly from the average strain rate. Therefore, the results of tensile impact tests must be expressed in terms of impact velocity and not in terms of strain rate.

In order to determine the influence of pure strain rate on the properties of materials, it is necessary to conduct a test in which propagation effects are either eliminated or very markedly minimized. To this end, special equipment has been devised.[594] A tubular specimen was employed in such a manner that a uniform circumferential stress was introduced. The stress was obtained by means of fluid pressure applied within the tubular specimen in such a manner that strain rates up to approximately 200 in. per in. per sec were attained. These tests were made on MS, HTS, and STS ship plate. Since the specimens consisted of thin-walled tubes approximately 0.013 in. thick, inhomogeneities and segregation in the structure were found to be highly influential on the results of the test.

The results of the uniaxial strain rate tests have shown that for these particular materials the ultimate strength and proportional limit increases with increasing strain rate in the range from approximately zero to about 200 in. per in. per sec. Evidence has been presented to show that the ultimate strength attains an approximately constant value at rates of strain as high as about 200 in. per in. per sec. The proportional limit becomes equal to the ultimate strength at a rate of strain of about 70 in. per in. per sec. The values of maximum uniform strain at rupture were quite scattered; therefore, no relation could be found between these measurements and the rate of strain. It was of considerable interest to note in these tests that the ultimate strength of these three materials as determined with the tubular specimens at a strain rate of about 200 in. per in. per sec. was about the same as that determined in the tensile impact tests in the range of impact velocities of 25 to 200 fps. Some of the specimens of the MS ship plate cracked open prematurely in both static and dynamic tests. Izod impact tests were made on these same materials, and there did not appear to be any correlation with premature cracking in the tubular type of specimens. As a result of these investigations it appears that the increase of ultimate strength resulting from dynamic effects is about the same whether determined under conditions of high pure rate of strain or under tensile impact conditions.

The pure strain rate tests just described were applied to samples taken from two 76-mm gun tubes which showed markedly different behavior when ruptured by detonation of a high-explosive shell in the bore of the tube.[595] One of these tubes failed in a ductile manner while the other fragmented badly. The dynamic tests were made at a strain rate as high as 190 in. per in. per sec. Static tensile tests and Izod impact tests made on these materials had revealed the expected differences in the two gun tubes, one of which was slack quenched, quenched in solid, the other fully quenched, quenched as a tube. This fact

was not stated in the progress report.[595] Tests on the uniaxial thin-walled specimens at high strain rates showed that the gun tube which failed in a brittle manner had a very low uniform maximum strain, while the gun tube that failed in a ductile manner had a much higher uniform maximum strain. No better differentiation was obtained by these tests, however, than was obtained by ordinary tensile and impact tests.

Rapid Loading

The research up to this point was concerned with the influence of impact velocity and strain rate on the properties of metals and alloys. As a result of these investigations, a reasonably clear picture has been secured of the conditions prevailing under an impact type of loading. This condition involves an almost instantaneous setting into motion of some part of a structural member. Such a condition gives rise to the propagation of strain waves which, under certain conditions, may be disastrous to the structure. It was shown that with impact loading and with high strain rates the proportional limit and ultimate strength are greater than with static loading. With this knowledge one may examine the dynamic loading conditions which may prevail in the practical case.

One is confronted with the difficulty of finding very many structures in practice that are subject to true impact loading. Usually the load may be applied rapidly to some specific value, maintained at that value for a specified length of time, and released or changed to another value. Since it has been shown that the proportional limit is higher for high rates of strain than for static loading, one may question the time for which a rapidly applied load can be sustained without causing permanent deformation.

This problem has been considered in a preliminary investigation.[596] Very simple equipment was assembled for this study and, while it was inadequate for a precise examination of such phenomena, preliminary indications were obtained which appear to be significant. The results showed that it was possible to maintain a stress which had been applied rapidly for a short time without causing plastic deformation even though that stress was above the static elastic limit.

It was recognized that in order to obtain accurate information on this subject, with a shorter time interval for loading and time of sustained load, special equipment was required. Therefore a hydropneumatic machine was designed to fulfill the requirements of this investigation.[597] The machine was designed to attain a tensile load of 20,000 lb in approximately 5 msec and to permit that load or any fraction of it to be maintained for any desired length of time. Provision was made for making the proper record of the tests.

Summary

The investigations covered in this research were concerned primarily with impact in tension, compression, and bending. The theoretical relations concerning the propagation of plastic strain were presented and checked experimentally. In addition, specific data were obtained on the influence of impact velocity on the tensile properties of a relatively large number of metals and alloys. Investigations were made also on the influence of strain rate on the properties of a few ferrous alloys.

The foregoing work led to preliminary tests in the study of rapid loading as distinguished from impact loading. This approach appears to have the greatest practical significance and, if further work were to be done in the field of the dynamic properties of metals and alloys, this phase should be pursued. Equipment was designed by which such studies can be carried on.

The foregoing discussion was taken from the final report on Project NRC-82 (NS-109) prepared by California Institute of Technology.[598] As there was no promise of the work's yielding results of practical significance in the war effort, the project was terminated in December 1944. The investigation with respect to the effect of explosive impact on armor plate, ship plate, and aircraft materials is by no means completed, however. It is the belief of members of the staff of Division 18 that the attainable velocities were too low and that the simplest way to attain explosive velocity is to use explosives. This procedure is discussed in Sections 2.2 and 6.1.2 in connection with the development of a direct explosion test for armor and ship plate.

In April 1945, the Office of the Chief of Engineers requested NDRC to undertake further work on the dynamic properties of steels used in reinforcing concrete (Control No. CE-36.01). It was proposed that "additional data on impact stresses in the plastic range . . . be developed, particularly the increase in elastic limit for load applied in 0.005 sec or less." This work was not undertaken for the same reason that the original project was terminated.

9.3.3 Effects of Impurities on the Ferromagnetism of Nonferrous Alloys

Instrument housings and various parts in the neighborhood of aircraft instruments of the magnetic type need to have low magnetic susceptibility and magnetic moment in order that the instruments may give correct indications. Brass and bronze castings, wrought brass, and cast and wrought aluminum alloys are commonly used in these locations, since they are but slightly magnetic. However, all these alloys contain small amounts of iron, and, when they are prepared from secondary metals, it is difficult and impractical to keep the iron content exceedingly low or to hold it at any exact level. The iron content is the principal cause of magnetism.

At the request of Frankford Arsenal, the Office of the Chief of Ordnance requested NDRC to investigate the effects of impurities on the ferromagnetism of nonferrous alloys. Project NRC-79 (OD-156) was established at Lehigh University with the aim of determining the degree of magnetic interference exerted by the common alloys with various iron contents, and the possibility of controlling this influence by variation in composition, heat treatment, aging, and plastic deformation.

Few common nonferrous alloys regularly incorporate relatively large amounts of iron as an essential alloying element to confer strength, as in manganese bronze or manganese aluminum bronze. These are covered by Federal Specification QQB-726, compositions B and C, for castings. These alloys exert too much magnetic interference to be applicable to the purposes under examination.

The common copper-base castings are the bronzes, containing 3 to 8 per cent of tin, 3 to 10 per cent of zinc, and up to 10 per cent of lead, with iron usually in the range of 0.05 to 0.25 per cent. Such alloys are covered by Federal Specifications QQB-691a, compositions 2 and 11.

In the as-cast condition, it may be necessary to hold the iron content below 0.10 per cent to reach the desired degree of freedom from magnetism. In different castings, or with different rates of cooling of the castings, irregularities in behavior may appear, since the iron in solid solution is relatively ineffective; whereas, if it is thrown out of solution, as by slow cooling of the casting, it becomes effective in producing magnetism. With very high iron content, cold working, as by cold rolling or cold forging, may also throw iron out of solution.

However, by heating the casting to 1475 to 1600 F, most or all of the iron is taken into solution and can be retained in solution by quenching from such a temperature. This treatment induces satisfactory nonmagnetic behavior up to an iron content of about 0.30 per cent. Annealing the quenched alloys at 1200 F throws the iron out of solution and makes the tolerance revert to about 0.10 per cent; annealing at 1100 F reverts it to about 0.20 per cent.

The yellow brass casting alloy QQB-621, composition B, behaves much as do the bronze castings, but, in the solution-quenched condition, can tolerate a bit more iron.

Rolled yellow brass, QQB-611a, composition C, with about 2/3 copper, 1/3 zinc, is much more magnetic for a given iron content than are the cast alloys studied. Without solution quenching it tolerates only about 0.04 per cent iron. Solution-quenched, it can tolerate 0.15 per cent. A stress-relieving anneal at 575 F of hard-rolled brass materially increases its magnetism. True annealing at 930 F increases it, but not so much as does the lower temperature. That is, at 930 F some of the iron is being taken into solution.

The plastic deformation produced by rolling or forging makes the iron come out of solution very much more readily than it does in a casting of comparable composition.

It is possible that this sensitiveness to iron may be connected with the presence of the beta copper-zinc phase in the alloy tested.

A few commercial aluminum alloys also have been studied. Commercial aluminum carries much higher iron content than the copper-base alloys do. However, a few compositions used for commercial sand and permanent mold castings and a couple of forging compositions were examined and found to show so little magnetism as to give no concern about their use. In such alloys the iron is probably combined with aluminum into compounds that are practically nonmagnetic. In one of the sand casting alloys tested, 1 per cent of iron was present without harmful results. The details of the methods used and the results of this investigation are given in four progress reports[599-602] and summarized in a final report.[603]

This project was transferred from NDRC to the Office of the Chief of Ordnance in May 1945 and is being continued by that office under a direct contract.

9.4 CONSERVATION, SUBSTITUTION, AND PROCESSING OF MISCELLANEOUS MATERIALS

Although most problems involving the conservation, substitution, or processing of various materials were studied by the War Metallurgy Committee at the request of the War Production Board, several survey projects in this field were conducted at the direct request of the Armed Services and advisory reports were issued for NDRC. These covered a variety of subjects such as the engineering applications of chromium plating, rivets and rivet steels, rare metal contacts, and the reclaiming of lead-bearing copper alloy scrap. The requests for these studies also asked for recommendations on the research necessary. In most of these cases, the survey projects were able to secure from industry sufficient information on the problems to obviate the necessity of establishing research projects.

Research projects were established on two conservation problems; the heat treatment of National Emergency [NE] steels and the hardenability of cast alloy steels. Although these projects were mentioned in connection with armor in Chapter 2 of this report, their objectives and results were not described.

9.4.1 Applications of Chromium Plating

In order to provide a basis for the establishment of research investigations on the use of chromium plating in war materiel, in March 1942 the Office of the Coordinator of Research and Development and the Bureau of Aeronautics, Navy Department, requested the War Metallurgy Committee to study the industrial applications of chromium plating. Under Survey Project SP-2, Industrial Application of Chromium Plating, a correlated abstract of approximately 300 articles and patents selected from some 10,000 was prepared. This review[604] does not cover new experimental work but is a useful summary of published and unpublished information dealing with the industrial nondecorative uses of chromium plating. It describes many successful applications for parts subject to severe wear, that is, gages, tools, dies, etc. While uses in war materiel are not described in detail, reference is made briefly to the use of chromium plating for the reduction of erosion in guns and for decreasing the wear of aircraft engines and propellors. To familiarize designers and engineers with the possibilities and limitations of the use of chromium plating, a revised edition of the report was distributed widely throughout industry by the War Metallurgy Committee.

Although no projects were established by Division 18 or the War Metallurgy Committee on this subject as a result of the survey, investigations of the use of chromium plating in guns were conducted by Watertown Arsenal and Division 1, NDRC.

9.4.2 Proposed Research on Rivets and Rivet Steels

At the request of the Coordinator of Research and Development, Navy Department, the War Metallurgy Committee established Survey Project SP-8 in August 1942 to review the Bureau of Ships Research Memorandum No 3-41, Rivet Rod and Rivets: The Relation of Chemical Composition to Their Physical and Metallurgical Properties, and Report No 3179-17A of the Materials Laboratory, Navy Yard, New York, and to appraise the proposed research project.

It was the consensus of the reviewers[605] that the development of a superior rivet steel was essentially a metallurgical problem which could be solved using the alloy elements available at that time. The use of the alloy steels proposed by the Navy Department was no longer feasible because the alloying elements needed were no longer readily available. It was believed, however, that the Navy Department was in the best position to decide whether a research program was advisable. It was estimated that an adequate program would cost approximately $20,000 and require six months for its completion. No project was established by Division 18 or the War Metallurgy Committee.

9.4.3 Rare Metal Electrical Contacts

In May 1942 the Conservation Branch, Resources and Production Division, Army Service Forces requested the War Metallurgy Committee to undertake a study of the current osmium situation, which had become critical. The yearly consumption of

osmium was about 2,400 ounces, yearly production was about 600 ounces, and stocks were approximately 1,000 ounces. It was evident that, unless consumption was curtailed sharply, military needs could not be supplied. The development of substitutes for osmium was recommended.

As a result of this request, Survey Project SP-16, Rare Metal Electrical Contacts, was carried out. Although it was found that the stock of osmium available for military and civilian use was about 6,100 ounces instead of 1,000 ounces, it was evident that the supply and demand had to be brought into balance to meet military needs. The report on the project[606] reviews the osmium situation and makes useful suggestions relative to the substitution, conservation, and increased supply. It was believed that research in this field would be better carried out by industry, and it was recommended that osmium be placed under allocation by the War Production Board to insure its most effective use.

Subsequently, the Conservation Branch, Production Division, Headquarters, Army Service Forces, requested a second report on this subject under their control number SOS-3, Possibility of Interchangeable Use of the Materials and Alloys of the Platinum Group, Silver, Tungsten, and Others, in Electrical Contacts. Survey Project SP-16 was, therefore, reactivated for the purpose of making the requested study. The report on this phase of the survey[607] reviews the various types of contact materials and the problems involved in the functioning of electrical contacts. The aim of the discussion of contact materials was to offer aid in the selection of a few promising materials for test in newly designed equipment and in considering possible substitutions. It is stressed that the complexity of the contact phenomena is such that final selections cannot be made from existing data and that actual tests of promising materials must be made in the specific device under operating conditions when possible. Otherwise very carefully simulated operating conditions must be imposed to determine if a proposed material is adequate.

9.4.4 Upgrading of Lead-Bearing Copper Alloy Scrap

Another survey made at the request of the Conservation Branch, Production Division, Headquarters, Army Service Forces was of methods of reclaiming lead-bearing copper alloy scrap for reuse. A special committee appointed by the War Metallurgy Committee studied this problem and submitted a report in March 1943.[608]

Three types of scrap were involved in the study: (1) screw machine turnings and borings, (2) miscellaneous cast bronze, cast red brass, and yellow brass with lead as a major constituent, and (3) high-leaded bronze such as railroad car bearings. The committee recommended that, in case the scrap was not being utilized in an economical manner, additional melting capacity be installed to handle the first type of scrap, and additional converter and fire-refining capacity be installed to handle the second and third types. It was stressed that the problem was not the lack of a suitable method to handle the scrap. The committee concluded that no research was necessary.

9.4.5 Heat Treatment of National Emergency Steels

The formulation and adoption of the NE steels to replace the standard steels and to conserve critical alloying elements was one of the outstanding metallurgical accomplishments of World War II. In order to establish proper heat treatments to utilize these steels to full advantage in ordnance materiel, more information was needed on their cooling rates. This investigation was undertaken by the Research Laboratories Division of General Motors Corporation under Project NRC-55, Heat Treatment of National Emergency Steels for Use in Tanks, Combat Cars, Gun Mounts, and Other Ordnance Matériel. Although the project was established on the recommendation of the War Metallurgy Committee, it was subsequently endorsed by the Office of the Chief of Ordnance and conducted under their control number OD-115.

To determine the cooling rates and cooling times, a procedure was worked out and special equipment constructed.[126] In addition, an accurate cooling curve temperature recorder was developed with the desired sensitivity for recording temperatures simultaneously at four positions in the test specimen.[124] In the preliminary phase of the investigation, the effects of composition and the degree of hardenability upon cooling rates along the length of the standard Jominy hardenability test bar, end-quenched from

1500 F and 1650 F, were determined for two NE steels, NE 9420 and NE 9445, as well as SAE 1115 and SAE 1045.[125] These data were obtained from cooling curve records produced by the same recording equipment to be used for studies of the quenching of rounds and plates and were necesary for an accurate correlation between cooling rates in the hardenability test bar and those in plates and rounds. In the final phase of the investigation, the cooling rates and cooling times in different round and plate sections quenched in water were studied. Data were taken at the center and at three other locations in 1-in., 2-in., 3-in., and 4-in. rounds of NE 9445 or NE 9450 steels, and at the center and at three other locations in ¼-in., ½-in., 1-in., 2-in., and 3-in. plate specimens of 0.34 per cent carbon armor plate steel. Also studied were quenching experiments for determining the effects of (1) the change of quenching temperature from 1525 F to 1650 F, (2) the presence or absence of scale prior to quenching, (3) the change of water temperature from 55 F to 75 F and 80 F, and (4) variation of water velocity over a range of from 0 to 1,000 fpm. The application of this work in the study of the metallurgy of armor is discussed briefly in Section 2.3.3 of this report.

These data permitted the correlation of cooling rates and cooling times in plate and round sections quenched in water with similar data on the standard Jominy end-quenched hardenability bars, and the preparation of usable charts showing this correlation.

9.4.6 Hardenability of Cast Alloy Steels

A project closely related to the studies of the heat treatment of NE steels and of equal value in the war effort was Project NRC-83A, Hardenability of Cast Steels for Use in Ordnance Matériel. The investigation was financed by the American Brake Shoe Company and was conducted under the general supervision of the War Metallurgy Committee. It was established in March 1944 with the objective of (1) determining the composition ranges, employing a minimum of strategic alloying elements, that would be satisfactory for the production of steel castings under Federal Specification QQ-S-681b, (2) investigating the minimum strategic alloy content that would be adequate for tank armor, in anticipation of the possible need for revision of cast armor specifications to effect further conservation of the alloys, and (3) examining the relationships between chemical composition, mechanical properties, tempering characteristics and hardenability for heat-treated cast steels.

The last of these objectives produced many data of wide applicability in the utilization of alloy steels to attain high strength and toughness. Of most general value are the hardenability data for the deeper hardening cast alloy steels. Thirty-three heat-treated cast alloy steels were made and tested. The program included the evaluation of mechanical properties at several hardness levels for quenched and tempered 1-in. rounds (tensile tests) and ¾-in. squares (Izod impact tests) and of hardenability as measured by the standard Jominy end-quench tests.[119] The application of the results of this investigation to the metallurgy of low-alloy homogeneous armor is also discussed in Section 2.3.2 of this report.

Although the investigation was closed as a correlation project for the NDRC at the end of World War II, it is being continued by the American Brake Shoe Company.

9.4.7 Acceptance Tests for Plain Carbon Steel Forgings

It was thought that a program of study on plain carbon steel forgings, similar to that carried out for gun tubes and discussed in Chapter 3 of this report, should yield information of considerable practical value to those making plain carbon steel forgings for the Armed Services and to those responsible for the writing of specifications for plain carbon steel forgings for ordnance matériel. At the request of the Office of the Chief of Ordnance under control number OD-114, Project NRC-58, Acceptance Tests for Plain Carbon Steel Gun Forgings and Other Ordnance Forgings, was established at Carnegie Institute of Technology in April 1943. The program covered a statistical analysis of the transverse ductility in plain carbon forging steel represented by SAE 1045 and included studies of the effect of the direction to fiber of forging, the effect of eight different heat treatments including normalizing, the effect of homogenization, the effect of the degree of forging upon the reduction in area, and the effect of banding.

A very complete metallurgical investigation was made of one plain carbon steel forging. In addition,

a thorough statistical study was made of tensile test data received from companies making forgings for the Armed Services.

On the average, the maximum variation of transverse reduction of area was found to be about as large in quenched and tempered plain carbon steel forgings as in alloy gun tube forgings. Attempts to reduce this variation significantly by high temperature homogenization treatments all failed.[609] The project was terminated in August 1944.

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402. *Examination of Enemy Matériel. Metallurgical Examination of Two Japanese Oxygen Cylinders*, H. L. Anthony, OSRD 3812, Progress Report M-303, Mellon Institute of Industrial Research, June 14, 1944. Div. 18-802.15-M1

403. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Naval Aircraft Gear Oil Pump*, L. H. Grenell, J. R. Cady, and others, OSRD 3836, Progress Report M-307, Battelle Memorial Institute, June 19, 1944. Div. 18-802.12-M5

404. *Examination of Enemy Matériel. Metallurgical Examination of Three Types of Japanese Aircraft Exhaust Valves and Two Types of Intake Valves*, C. E. Levoe, Howard C. Cross, and H. W. Gillett, OSRD 3838, Progress Report M-308, Battelle Memorial Institute, June 19, 1944. Div. 18-802.12-M4

405. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 63 Kilogram Bombs, Fuzes, and Gaines*, L. H. Grenell, J. R. Cady, and others, OSRD 3839, Progress Report M-309, Battelle Memorial Institute, June 19, 1944. Div. 18-802.21-M9

406. *Examination of Enemy Matériel. Metallurgical Examination of Six Rounds of Japanese 20 mm AP Ammunition*, L. H. Grenell, J. R. Cady, and others, OSRD 3843, Progress Report M-310, Battelle Memorial Institute, June 27, 1944. Div. 18-802.21-M10

407. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 25 mm Hotchkiss Incendiary and H.E. Incendiary, Tracer Rounds*, L. H. Grenell, J. R. Cady, and others, OSRD 3844, Progress Report M-314, Battelle Memorial Institute, July 3, 1944. Div. 18-802.21-M11

408. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Sakae-12 Engine Oil Tank*, L. H. Grenell, J. R. Cady, and others, OSRD 3845, Progress Report M-315, Battelle Memorial Institute, July 3, 1944. Div. 18-802.12-M6

409. *Examination of Enemy Matériel. Metallurgical Examination of Czechoslovakian Tank Armor Plate*, L. H. Grenell, J. R. Cady, and others, OSRD 3846, Progress Report M-316, Battelle Memorial Institute, July 3, 1944. Div. 18-803.11-M1

410. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 70 mm and 75 mm H.E. Ammunition*, L. H. Grenell, J. R. Cady, and others, OSRD 3894, Progress Report M-318, Battelle Memorial Institute, July 11, 1944. Div. 18-802.21-M14

411. *Examination of Enemy Matériel. Metallurgical Examination of Four Japanese 50 mm Grenades and Six Fuzes*, L. H. Grenell, J. R. Cady, and others, OSRD 3895, Progress Report M-319, Battelle Memorial Institute, July 11, 1944. Div. 18-802.21-M13

412. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 37 mm High Explosive Shells*, L. H. Grenell, J. R. Cady, and others, OSRD 3896, Progress Report M-320, Battelle Memorial Institute, July 11, 1944. Div. 18-802.21-M12

413. *Examination of Enemy Matériel. Metallurgical Examination and Performance Tests of a Japanese Yokogawa Aircraft Magnet*, L. H. Grenell, J. R. Cady, and others, OSRD 3891, Progress Report M-322, Battelle Memorial Institute, July 11, 1944. Div. 18-802.12-M7

414. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Navy 1 KVA Alternating Current Generator Repair Kit*, L. H. Grenell, J. R. Cady, and others, OSRD 3892, Progress Report M-323, Battelle Memorial Institute, July 11, 1944. Div. 18-802.3-M3

415. *Examination of Enemy Matériel. Metallurgical Examination of Armor Plate from Japanese Type* I *F "Oscar" Mark* II *SE Fighter*, L. H. Grenell, J. R. Cady, and others, OSRD 3893, Progress Report M-324, Battelle Memorial Institute, July 11, 1944. Div. 18-802.11-M1

416. *Examination of Enemy Matériel. A Metallurgical Examination of Two Japanese 7.7 mm Aircraft Machine Guns of 1938 and 1942*, E. W. Ganslein, C. A. Reichelderfer, and others, OSRD 3917, Progress Report M-325, Battelle Memorial Institute, July 18, 1944. Div. 18-802.23-M7

417. *Examination of Enemy Matériel. A Metallurgical Examination of Three 40 mm Japanese Naval Projectiles*, L. H. Grenell, J. R. Cady, and others, OSRD 3918, Progress Report M-326, Battelle Memorial Institute, July 18, 1944. Div. 18-802.21-M15

418. *Examination of Enemy Matériel. A Metallurgical Examination of Japanese .30 Caliber and .50 Caliber Disintegrating Cartridge Link Belts*, L. H. Grenell, J. R. Cady, and others, OSRD 3919, Progress Report M-327, Battelle Memorial Institute, July 18, 1944. Div. 18-802.21-M16

419. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Aircraft Oil Radiator*, L. H. Grenell, J. R. Cady, and others, OSRD 3920, Progress Report M-333, Battelle Memorial Institute, July 18, 1944. Div. 18-802.12-M8

420. *Examination of Enemy Matériel. Metallurgical Examination of Selected Parts from Japanese Type 100, Radial, 1450 H.P., Aircraft Engines*, L. H. Grenell, J. R. Cady, and others, OSRD 3921, Progress Report M-334, Battelle Memorial Institute, July 21, 1944. Div. 18-802.12-M10

421. *Examination of Enemy Matériel. Design Features and Performance Characteristics of the Japanese Hand and Electric Inertia Starter*, R. M. Nardone, OSRD 3922, Progress Report M-337, Battelle Memorial Institute, July 20, 1944. Div. 18-802.12-M9

422. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 81 mm High Explosive Light Mortar Shell Complete with Type 93 Fuze*, L. H. Grenell, J. R. Cady, and others, OSRD 3966, Progress Report M-339, Battelle Memorial Institute, July 27, 1944. Div. 18-802.21-M17

423. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Sakae-12 Aircraft Engine Mount*, L. H. Grenell, J. R. Cady, and others, OSRD 3967, Progress Report M-340, Battelle Memorial Institute, July 27, 1944. Div. 18-802.12-M11

424. *Examination of Enemy Matériel. Metallurgical Examination of Fuel Tank from Japanese Aircraft "Oscar,"* C. A. Reichelderfer, J. M. Blalock, and H. W. Gillett, OSRD 3999, Progress Report M-344, Battelle Memorial Institute, Aug. 7, 1944. Div. 18-802.14-M3

425. *Examination of Enemy Matériel. Metallurgical Investigation of German 170 mm Gun Tube*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4000, Progress Report M-346, Massachusetts Institute of Technology, Aug. 7, 1944. Div. 18-801.23-M9

426. *Examination of Enemy Matériel. Metallurgical and Chemical Examination of a Japanese Landing Gear and Wheel*, L. H. Grenell, J. R. Cady, and others, OSRD 4001, Progress Report M-347, Battelle Memorial Institute, Aug. 9, 1944. Div. 18-802.11-M2

427. *Examination of Enemy Matériel. Metallurgical Examination of Four Japanese 47 mm Armor Piercing, High Explosive Shells*, L. H. Grenell, J. R. Cady, and others, OSRD 4062, Progress Report M-349, Battelle Memorial Institute, Aug. 22, 1944. Div. 18-802.21-M18

428. *Examination of Enemy Matériel. Metallurgical Examination of Parts from a Japanese Sakae-12 Engine*, L. H. Grenell, J. R. Cady, and others, OSRD 4063, Progress Report M-350, Battelle Memorial Institute, Aug. 22, 1944. Div. 18-802.12-M12

429. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese 20 mm Aircraft Machine Gun*, L. H. Grenell, J. R. Cady, and others, OSRD 4064, Progress Report M-351, Battelle Memorial Instutite, Aug. 22, 1944. Div. 18-802.23-M8

430. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Army 105 mm H.E. Shell of 1938,* L. H. Grenell, J. R. Cady, and others, OSRD 4071, Progress Report M-355. Battelle Memorial Institute, Aug. 24, 1944. Div. 18-802.21-M19

431. *Examination of Enemy Matériel. Metallurgical Examination of a German Airspeed Indicator,* L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4072, Progress Report M-356, Battelle Memorial Institute, Aug. 24, 1944. Div. 18-801.'2-M1

432. *Examination of Enemy Matériel. Metallurgical Examination of Landing Gear Strut, Landing Wheel, and Tail Wheel Strut Assembly from Japanese Aircraft "Betty,"* C. A. Reichelderfer, J. M. Blalock, and others, OSRD 4073, Progress Report M-357, Battelle Memorial Institute, Aug. 24, 1944. Div. 18-802.11-M3

433. *Examination of Enemy Matériel. Metallurgical Examination of a German and a Japanese Altimeter*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4113, Progress Report M-358, Battelle Memorial Institute, Sept. 7, 1944. Div. 18-801.12-M3

434. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 75 mm Armor-Piercing, High Explosive Howitzer Rounds*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4089, Progress Report M-359, Battelle Memorial Institute, Aug. 29, 1944. Div. 18-802.21-M20

435. *Examination of Enemy Matériel. Metallurgical Examination of a German Aircraft Master Compass and a Pilot (Repeater) Compass*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4090, Progress Report M-360, Battelle Memorial Institute, Aug. 29, 1944. Div. 18-801.12-M2

436. *Examination of Enemy Matériel. Metallurgical Examination of Four Different Types of Japanese Aircraft Spark Plugs*, L. H. Grenell, J. R. Cady, and others, OSRD 4125, Progress Report M-362, Battelle Memorial Institute, Sept. 7, 1944. Div. 18-802.12-M13

437. *Examination of Enemy Matériel. Metallurgical Examination of Captured Enemy Pressure Vessels*, H. L. Anthony, OSRD 4126, Progress Report M-363, Mellon Institute of Industrial Research, Sept. 7, 1944. Div. 18-801.13-M1

438. *Examination of Enemy Matériel. Metallurgical Investigation of Two 50 mm German Tank Gun Tubes, Breech Rings and Breech Ring Locking Collars*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4135, Progress Report M-364, Battelle Memorial Institute, Sept. 12, 1944. Div. 18-801.23-M10

439. *Examination of Enemy Matériel. Metallurgical Examination of Two Japanese Aircraft Bank and Turn Indicators*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4127, Progress Report M-367, Battelle Memorial Institute, Sept. 7, 1944. Div. 18-802.13-M1

440. *Examination of Enemy Matériel. Luminescence of Enemy Aircraft Instrument Dials*, J. R. Devore, OSRD 4145, Progress Report M-368, New Jersey Zinc Co., Sept. 7, 1944. Div. 18-802.13-M2

441. *Examination of Enemy Matériel. Metallurgical Examination of Two Japanese 140 mm Naval Projectiles*, L. H. Grenell, J. R. Cady, and others, OSRD 4131, Progress Report M-372, Battelle Memorial Institute, Sept. 14, 1944. Div. 18-802.21-M21

442. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Aircraft 12.7 mm "Browning" Machine Gun*, L. H. Grenell, J. R. Cady, and others, OSRD 4178, Progress Report M-376, Battelle Memorial Institute, Sept. 25, 1944. Div. 18-802.23-M9

443. *Examination of Enemy Matériel. Metallurgical Examination of Airframe Sections from "Zeke," "Val," "Lily," and "Dinah" Japanese Planes*, L. H. Grenell, J. R. Cady, and others, OSRD 4179, Progress Report M-377, Battelle Memorial Institute, Sept. 25, 1944. Div. 18-802.11-M4

444. *Examination of Enemy Matériel. Examination of Diaphragm and Gasket from Japanese Aircraft Fuel Pump*, R. G. Chollar, F. C. Croxton, and H. W. Gillett, OSRD 4180, Progress Report M-378, Battelle Memorial Institute, Sept. 26, 1944. Div. 18-802.14-M4

445. *Examination of Enemy Matériel. Metallurgical Examination of Two German MG-151 Aircraft Machine Gun Mounts*, L. H. Grenell, J. R. Cady, and others, OSRD 4214, Progress Report M-383, Battelle Memorial Institute, Oct. 7, 1944. Div. 18-801.23-M11

446. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Sakae-21 Aircraft Engine*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4234, Progress Report M-384, Battelle Memorial Institute, Oct. 7, 1944. Div. 18-802.12-M14

447. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese "Zeke" Aircraft Volt Box*, L. H. Grenell, J. R. Cady, and others, OSRD 4215, Progress Report M-386, Battelle Memorial Institute, Oct. 7, 1944. Div. 18-802.12-M15

448. *Examination of Enemy Matériel. Metallurgical Investigation of German 105 mm Gun Tube*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4251, Progress Report M-390, Battelle Memorial Institute, Oct. 7, 1944. Div. 18-801.23-M12

449. *Examination of Enemy Matériel. Metallurgical Examination of Airframe Sections from Japanese Aircraft "Jill,"* C. E. Heussner, A. B. Westerman, and H. W. Gillett, OSRD 4252, Progress Report M-391, Battelle Memorial Institute, Oct. 7, 1944. Div. 18-802.11-M5

450. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Oxygen and Carbon Dioxide Cylinders*, H. L. Anthony, OSRD 4267, Progress Report M-394, Battelle Memorial Institute, Oct. 17, 1944. Div. 18-802.15-M2

451. *Examination of Enemy Matériel. Metallurgical Examination of Oil Cooler from Japanese Aircraft "Betty,"* E. M. Smith, B. D. Gonser, and H. W. Gillett, OSRD 4279, Progress Report M-395, Battelle Memorial Institute, Oct. 17, 1944. Div. 18-802.12-M16

452. *Examination of Enemy Matériel. Examination of Japanese Aircraft Tires and Tubes*, OSRD 4280, Progress Report M-396, Battelle Memorial Institute, Oct. 17, 1944. Div. 18-802.11-M6

453. *Examination of Enemy Matériel. Metallurgical Examination of a German and a Japanese Aircraft Rate of Climb Indicator*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4281, Progress Report M-397, Battelle Memorial Institute, Oct. 17, 1944. Div. 18-801.12-M4

454. *Examination of Enemy Matériel. Metallurgical Examination of a German Aircraft Course Meter*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4315, Progress Report M-399, Battelle Memorial Institute, Nov. 8, 1944. Div. 18-801.12-M5

455. *Examination of Enemy Matériel. Corrosion Resistance of a Steel Piston and a Magnesium Casting from a Japanese Oleo Landing Strut*, L. H. Grenell, J. R. Cady, and others, OSRD 4316, Progress Report M-400, Battelle Memorial Institute, Nov. 8, 1944. Div. 18-802.11-M7

456. *Examination of Enemy Matériel. Metallurgical Examination of Six German Explosive Bomb Rack Bolts*, L. H. Grenell, J. R. Cady, and others, OSRD 4317, Progress Report M-401, Battelle Memorial Institute, Nov. 8, 1944. Div. 18-801.13-M2

457. *Examination of Enemy Matériel. Metallurgical Examination of a German MG-42, 7.92 mm Machine Gun*, L. H. Grenell, J. R. Cady, and others, OSRD 4358, Progress Report M-403, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-801.23-M13

458. *Examination of Enemy Matériel. Metallurgical Examination of Six Grades of Swedish Carbide Tool Tips*, S. L. Hoyt, E. B. T. Kindquist, and H. W. Gillett, OSRD 4387, Progress Report M-410, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-803.2-M2

459. *Examination of Enemy Matériel. Metallurgical Examination of Parts from an Aichi V-12 Japanese Aircraft Engine*, L. H. Grenell, J. R. Cady, and others, OSRD 4359, Progress Report M-411, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-802.12-M17

460. *Examination of Enemy Matériel. Metallurgical Examination of German Mechanical and Electrical Aircraft Tachometers*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4360, Progress Report M-412, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-801.12-M7

461. *Examination of Enemy Matériel. Metallurgical Examination of the Instrument Panel of a Jumo 211-B Direct Gasoline Injection Engine from a Junkers-88 German Bomber*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4364, Progress Report M-415, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-801.12-M6

462. *Examination of Enemy Matériel. Japanese Drift Meter or Bomb Sight*, L. H. Grenell, J. R. Cady, and others, OSRD 4365, Progress Report M-416, Battelle Memorial Institute, Nov. 13, 1944. Div. 18-802.13-M3

463. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Army 47 mm H. E. Projectiles*, L. H. Grenell, J. R. Cady, and others, OSRD 4366, Progress Report M-417, Battelle Memorial Institute, Nov. 25, 1944. Div. 18-802.21-M22

464. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Propeller Blades*, L. H. Grenell, J. R. Cady, and others, OSRD 4367, Progress Report M-418, Battelle Memorial Institute, Nov. 25, 1944. Div. 18-802.15-M3

465. *Examination of Enemy Matériel. Metallurgical Examination of Three Japanese Aircraft Landing Hooks*, L. H. Grenell, J. R. Cady, and others, OSRD 4388, Progress Report M-419, Battelle Memorial Institute, Nov. 25, 1944. Div. 18-802.11-M8

466. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Kinsei-43 Aircraft Engine*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4420, Progress Report M-422, Battelle Memorial Institute, Dec. 4, 1944. Div. 18-802.12-M18

467. *Examination of Enemy Matériel. Metallurgical Examination of a Gyro Compass from a Japanese Aircraft "VAL," Mark I*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4421, Progress Report M-425, Battelle Memorial Institute, Dec. 4, 1944. Div. 18-802.13-M5

468. *Examination of Enemy Matériel. Metallurgical Examination of a German Aircraft Fuel Consumption Meter and a Blinker-Type Oxygen Flow-Meter*, L. R. Jackson, W. W. Beaver, and H. W. Gillett, OSRD 4422, Progress Report M-426, Battelle Memorial Institute, Dec. 4, 1944. Div. 18-802.13-M4

469. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Bomb Hoist and Release*, L. H. Grenell, J. R. Cady, and others, OSRD 4423, Progress Report M-428, Battelle Memorial Institute, Dec. 6, 1944. Div. 18-802.15-M4

470. *Examination of Enemy Matériel. Metallurgical Examination of Airframe Sections from Japanese Aircraft*, L. H. Grenell, J. R. Cady, and others, OSRD 4429, Progress Report M-429, Battelle Memorial Institute, Dec. 6, 1944. Div. 18-802.11-M9

471. *Examination of Enemy Matériel. Metallurgical Examination of Oleo Landing Strut and Wheel from Japanese "Sally" Mark* II, L. H. Grenell, J. R. Cady, and others, OSRD 4424, Progress Report M-430, Battelle Memorial Institute, Dec. 6, 1944. Div. 18-802.11-M10

472. *Examination of Enemy Matériel. Metallurgical Investigation of German 170 mm Gun Tubes*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4463, Progress Report M-433, Battelle Memorial Institute, Dec. 12, 1944. Div. 18-801.23-M14

473. *Examination of Enemy Matériel. Metallurgical Examination of Two Japanese Mechanical Impact Fuzes and Containers*, L. H. Grenell, J. R. Cady, and others, OSRD 4454, Progress Report M-436, Battelle Memorial Institute, Dec. 8, 1944. Div. 18-802.21-M23

474. *Examination of Enemy Matériel. Metallurgical Examination of Parts from a Japanese Mamoru-11 Aircraft Engine*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4455, Progress Report M-437, Battelle Memorial Institute, Dec. 8, 1944. Div. 18-802.12-M19

475. *Examination of Enemy Matériel. Metallurgical Investigation of German 150 mm. Gun Tube*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4464, Progress Report M-438, Battelle Memorial Institute, Dec. 12, 1944. Div. 18-801.23-M15

476. *Examination of Enemy Matériel. Metallurgical Examination of Tail Wheel Assembly and Landing Gear Hydraulic Retracting Strut from a Japanese Aircraft "Dinah,"* L. H. Grenell, J. R. Cady, and others, OSRD 4465, Progress Report M-441, Battelle Memorial Institute, Dec. 8, 1944. Div. 18-802.11-M11

477. *Examination of Enemy Matériel. Metallurgical Examination of a German 7.92 mm MG-17 Aircraft Machine Gun*, L. H. Grenell, J. R. Cady, and others, OSRD 4507, Progress Report M-443, Battelle Memorial Institute, Dec. 19, 1944. Div. 18-801.23-M16

478. *Examination of Enemy Matériel. Metallurgical Examination of an H.E. 15 cm Japanese Naval Projectile*, L. H. Grenell, J. R. Cady, and others, OSRD 4548, Progress Report M-448, Battelle Memorial Institute, Jan. 5, 1945. Div. 18-802.21-M24

479. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 75 mm AA Ammunition*, L. H. Grenell, J. R. Cady, and others, OSRD 4563, Progress Report M-449, Battelle Memorial Institute, Jan. 8, 1945. Div. 18-802.21-M25

480. *Examination of Enemy Matériel. Metallurgical Examination of Two Welded Aluminum Sections from a German Mine.* L. H. Grenell, J. R. Cady, and others, OSRD 4549, Progress Report M-453, Battelle Memorial Institute, Jan. 5, 1945. Div. 18-801.3-M4

481. *Examination of Enemy Matériel. Metallurgical Examination of a Type 91, Change 3, 18-Inch Japanese Torpedo*, L. H. Grenell, J. R. Cady, and others, OSRD 4593, Progress Report M-457, Battelle Memorial Institute and Mellon Institute of Industrial Research, Jan. 18, 1945. Div. 18-802.24-M2

482. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Aircraft Armor Plate*, L. H. Grenell, J. R. Cady, and others, OSRD 4597, Progress Report M-464, Battelle Memorial Institute, Jan. 20, 1945. Div. 18-802.11-M12

483. *Examination of Enemy Matériel. Metallurgical Investigation of German 50 mm Gun Tubes*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4695, Progress Report M-473, Battelle Memorial Institute, Feb. 12, 1945. Div. 18-801.23-M17

484. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 37 mm A.P., H.E. Ammunition*, L. H. Grenell, J. R. Cady, and others, OSRD 4696, Progress Report M-474, Battelle Memorial Institute, Feb. 12, 1945. Div. 18-802.21-M26

485. *Examination of Enemy Matériel. Metallurgical Examination of the Hardware from Japanese and German Parachute Harnesses*, L. H. Grenell, J. R. Cady, and others, OSRD 4697, Progress Report M-475, Battelle Memorial Institute, Feb. 12, 1945. Div. 18-801.13-M3

486. *Examination of Enemy Matériel. Metallurgical Examination of Armor Plate from Japanese Aircraft "Betty,"* L. H. Grenell, J. R. Cady, and others, OSRD 4776, Progress Report M-483, Battelle Memorial Institute, Mar. 3, 1945. Div. 18-802.11-M13

487. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Electrical Cable*, L. H. Grenell, J. R. Cady, and others, OSRD 4777, Progress Report M-485, Battelle Memorial Institute, Mar. 3, 1945. Div. 18-802.3-M4

488. *Examination of Enemy Matériel. Metallurgical Examination of Captured Japanese Aluminum Pressure Vessels Used for the Storage of Oxygen*, H. L. Anthony, OSRD 4812, Progress Report M-486, Battelle Memorial Institute, Mar. 5, 1945. Div. 18-802.3-M5

489. *Examination of Enemy Matériel. Metallurgical Examination of Two Japanese Kasei Engines, Models 11 and 15*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4826, Progress Report M-488, Battelle Memorial Institute, Mar. 12, 1945. Div. 18-802.12-M20

490. *Examination of Enemy Matériel. Metallurgical Examination of a Japanese Model 92 Machine Gun*, L. H. Grenell, J. R. Cady, and others, OSRD 4827, Progress Report M-489, Battelle Memorial Institute, Mar. 12, 1945. Div. 18-802.23-M10

491. *Metallurgical Examination of Enemy Matériel. Metallurgical Investigation of German 75 mm Gun Tubes*, E. L. Bartholomew, Jr., M. S. Burton, and F. R. Evans, OSRD 4913, Progress Report M-498, Battelle Memorial Institute, Apr. 4, 1945. Div. 18-801.23-M18

492. *Examination of Enemy Matériel. Metallurgical Examination of Armor Plate from Japanese Aircraft "Lily 2,"* L. H. Grenell, J. R. Cady, and others, OSRD 4914, Progress Report M-501, Battelle Memorial Institute, Apr. 6, 1945. Div. 18-802.11-M14

493. *Examination of Enemy Matériel. Metallurgical Examination of German MP-431/1 7.92 mm Machine Pistol*, L. H. Grenell, J. R. Cady, and others, OSRD 4915, Progress Report M-502, Battelle Memorial Institute, Apr. 6, 1945. Div. 18-801.23-M19

494. *Examination of Enemy Matériel. Metallurgical Examination of German Tank Track Links and Pins*, L. H. Grenell, J. R. Cady, and others, OSRD 4916, Progress Report M-503, Battelle Memorial Institute, Apr. 6, 1945. Div. 18-801.24-M2

495. *Examination of Enemy Matériel. Metallurgical Examination of Japanese Sakae-12 Engine No. 124676*, L. H. Grenell, J. R. Cady, and H. W. Gillett, OSRD 4982, Progress Report M-504, Battelle Memorial Institute, Apr. 17, 1945. Div. 18-802.12-M21

496. *Examination of Enemy Matériel. Metallurgical Examination of Japanese 30 mm H.E. Incendiary and H.E. Tracer Ammunition*, L. H. Grenell, J. R. Cady, and others, OSRD 4917, Progress Report M-506, Battelle Memorial Institute, Apr. 6, 1945. Div. 18-802.21-M27

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498. *Examination of Enemy Matériel. Metallurgical Examination of Landing Wheel and Strut, and Wing Sections, and Components from Japanese Aircraft, "Frances,"* A. deS. Brasunas and D. O. Leeser, OSRD 5020, Progress Report M-513, Battelle Memorial Institute, May 1, 1945. Div. 18-802.11-M15

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599. *Investigation of the Effects of Impurities on the Ferromagnetism of Non-Ferrous Alloys*, Allison Butts and J. H. Frye, Jr., OSRD 3694, Progress Report M-279, Lehigh University, May 20, 1944. Div. 18-902.2-M1

600. *Investigation of the Effect of Impurities on the Ferromagnetism of Non-Ferrous Alloys*, Allison Butts, J. H. Frye, Jr., and P. L. Reiber, Jr., OSRD 4056, Progress Report M-335, Lehigh University, Aug. 24, 1944. Div. 18-902.2-M2

601. *Investigation of the Effects of Impurities on the Ferromagnetism of Non-Ferrous Alloys*, Allison Butts and P. L. Reiber, Jr., OSRD 4442, Progress Report 407, Lehigh University, Dec. 4, 1944. Div. 18-902.2-M3

602. *Investigation of the Effects of Impurities on the Ferromagnetism of Non-Ferrous Alloys*, Allison Butts and P. L. Reiber, Jr., OSRD 4833, Progress Report M-479, Lehigh University, Mar. 20, 1945. Div. 18-902.2-M4

603. *Investigation of the Effects of Impurities on the Ferromagnetism of Non-Ferrous Alloys*, P. L. Reiber, Jr., and Allison Butts, OSRD 5471, Progress Report M-548, Lehigh University, Aug. 20, 1945. Div. 18-902.2-M5

604. *Industrial Applications of Chromium Plating*, M. Kolodney OSRD 1074, Advisory Report M-26, National Academy of Sciences, Nov. 27, 1942. Div. 18-900-M1

605. *Proposed Research Project: Rivets and Rivet Steels*, OSRD 1162, Advisory Report M-42, National Academy of Sciences, Jan. 22, 1943. Div. 18-900-M2

606. *Osmium*, E. M. Wise, OSRD 1750, Advisory Report M-134, National Academy of Sciences, Aug. 27, 1943. Div. 18-902.4-M1

607. *Possibilities of Interchangeable Use of the Materials and Alloys of the Platinum Group, Silver, Tungsten, and Others in Electrical Contacts*, E. M. Wise, OSRD 5163, Advisory Report M-499, National Academy of Sciences, May 30, 1945. Div. 18-902.4-M2

608. *Upgrading of Lead-Bearing Copper Alloy Scrap*, OSRD 1244, Advisory Report M-55, National Academy of Sciences, Mar. 5, 1943. Div. 18-900-M3

609. *Acceptance Tests for Plain Carbon Steel Gun Forgings and Other Ordnance Forgings*, R. F. Mehl and A. H. Grobe, OSRD 5018, Final Report M-466, Carnegie Institute of Technology, May 3, 1945. Div. 18-301-M3

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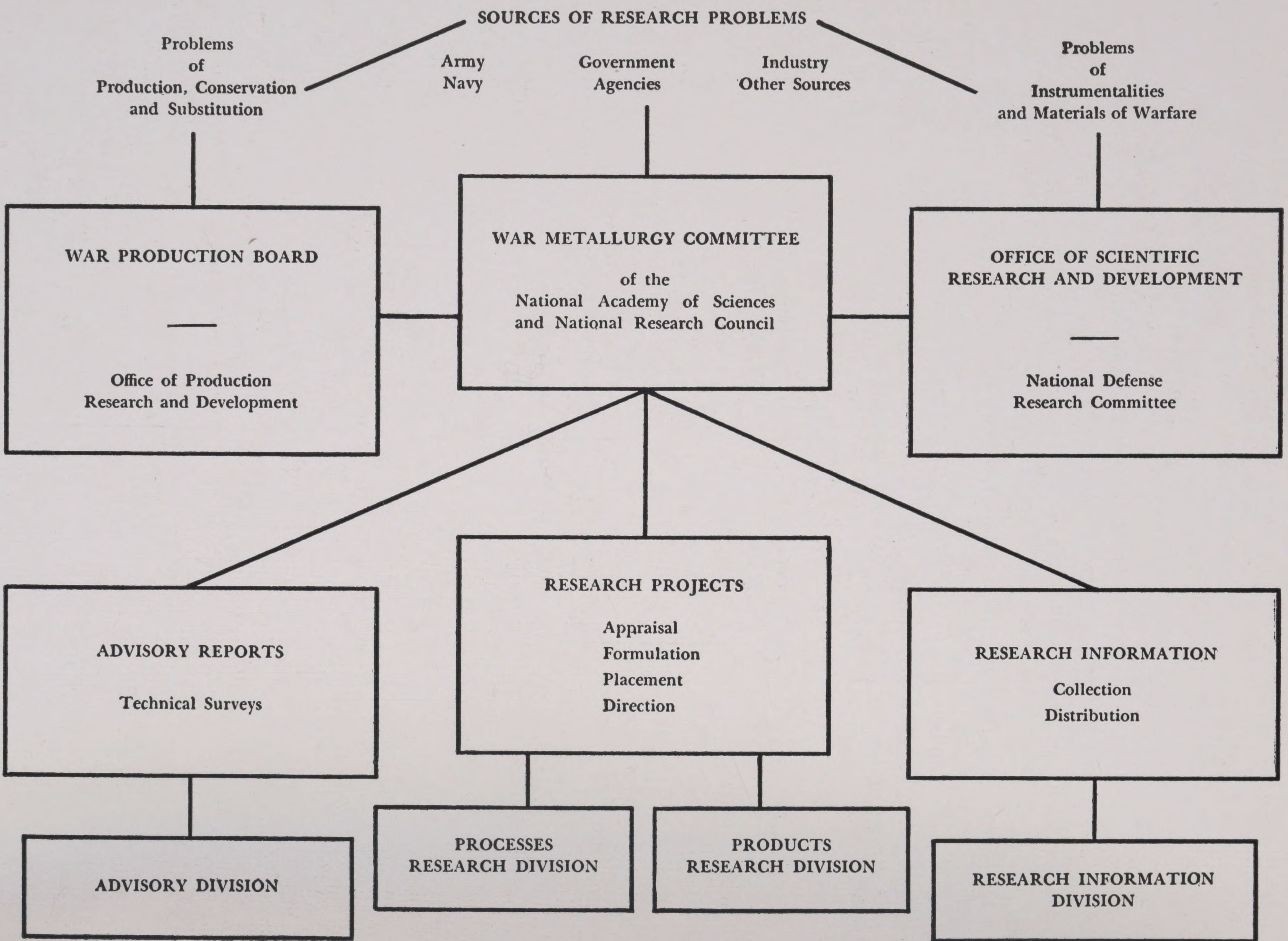

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ARMY AND NAVY PROJECTS ASSIGNED TO DIVISION 18
AND THE DIVISION 18 PROJECTS PERTAINING TO EACH

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Army or Navy Control Number	*Army or Navy Title and Division 18, NDRC Project Pertaining Thereto*
AC-4	Development of Beryllium Alloys Applicable to Construction of Aircraft NRC-7 Beryllium-Aluminum Alloys for Engine Parts
AC-6	Armor: Development of Nonmagnetic Armor B-104 & B-208 Development of Nonmagnetic Armor Steel
AC-75	Development and Testing of Solid Propellants and Motors for Jet Propulsion Devices Requiring Large Propellant Grains NRC-88 Metal and Ceramic Materials for Jet Propulsion Devices
AC-77	Examination of Enemy Aircraft Matériel NRC-32 Examination of Enemy Matériel
AC-86	Magnesium Alloys for Oxygen Systems Project not undertaken
AN-13	Development of Noncontaminating Fifty-Five Gallon Drums for Petroleum Products Project not undertaken
CE-36.01	Investigations on Behavior of Metals Under Dynamic Conditions Project not undertaken (See NS-109)
N-101	The Corrosion-Fatigue Failure of Aircraft Control Cables NRC-15 Corrosion-Fatigue Failure of Aircraft Control Cables
N-102	Heat-Resisting Metals for Gas Turbine Parts SP-5 Current Data on Selected Alloys Suitable for High-Temperature Service in Gas Turbine and Supercharger Parts NRC-8 Heat-Resisting Metals for Gas Turbine Parts NRC-41 Heat Treatment of High-Temperature Alloys NRC-90 Weldability of Heat-Resisting Alloys
N-119	Examination of Enemy Matériel NRC-32 Examination of Enemy Matériel
NA-100	Beryllium-Aluminum Alloys for Engine Parts NRC-7 Beryllium-Aluminum Alloys for Engine Parts
NA-115	Effects of Shot Blasting on Mechanical Properties of Steel NRC-40 Effects of Shot Blasting on Mechanical Properties of Steel NRC-78 Study of Effects of Surface Prestressing on Dynamic Properties of Metals
NA-119	Investigation of the Effect of Impurities in Aluminum Alloys SP-17 Effects of Impurities in Aluminum Alloys
NA-126	Forming of Aluminum Alloys NRC-43 Correlation of Information Available on the Fabrication of Aluminum Alloys SP-18 Fatigue and Impact Characteristics and Notch Effect in Tension of Artificially-Aged Aluminum Alloys
NA-137	High Temperature Properties of Light Alloys SP-15 High Temperature Properties of Light Alloys
NA-144	Properties and Heat Treatment of Magnesium Alloys NRC-21 Properties and Heat Treatment of Magnesium Alloys
NA-145	Fatigue Properties of Magnesium Alloys and Structures NRC-22 Fatigue Properties of Magnesium Alloys and Structures
NA-146	Formability of Magnesium Alloy Sheet NRC-44 Formability of Magnesium Alloy Sheet
NA-147	Physical and Stress-Corrosion Properties of Magnesium Alloy Sheet NRC-67 Physical and Stress-Corrosion Properties of Magnesium Alloy Sheet
NA-148	Deformation Characteristics of Magnesium Alloys NRC-70 Deformation Characteristics of Magnesium Alloys
NA-149	Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, I NRC-51 Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, I
NA-150	Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, II NRC-52 Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, II

Army or Navy Control Number	*Army or Navy Title and Division 18, NDRC Project Pertaining Thereto*
NCG-100	The Influence of Peening on Weldments Project not undertaken
NO-11	Structural Defense Testing Facilities for Armor NRC-82 Behavior of Metals Under Dynamic Conditions
NO-B-13	Nonmagnetic Armor or Armor of Modified Magnetic Properties B-104 & B-208 Development of Nonmagnetic Armor Steel
NO-159	Bimetallic Copper Steel Rotating Bands for Projectiles NRC-60 Bimetallic Rotating Bands for Projectiles
NS-109	Properties of Materials at High Rates of Loading NRC-82 Behavior of Metals Under Dynamic Conditions
NS-255	Weldability of Steel for Hull Construction NRC-25 Direct Explosion Test for Welded Armor and Ship Plate NRC-86 Weldability of Steel for Hull Construction NRC-87 Investigation of Metallurgical Quality of Steels Used for Hull Construction
NS-304	Residual Stresses in Ship Welding NRC-64 Residual Stresses in Ship Welding NRC-89 Fatigue Tests of Ship Welds
NS-305	History of Residual Stresses on Welded Ships NRC-74 History of Residual Stresses in Welded Ships
NS-306	Behavior of Steel Under Multiaxial Stresses NRC-75 Behavior of Steel Under Conditions of Multiaxial Stresses and Effect of Welding and Temperature on This Behavior
NS-307	Behavior of Steel Under Conditions of Multiaxial Stress and the Effect on This Behavior of Metallographic Structure and Chemical Composition NRC-77 Behavior of Steel Under Conditions of Multiaxial Stress and the Effect on This Behavior of Metallographic Structure and Chemical Composition
NS-336	Investigation of Cleavage Fracture Sensitivity of Steel NRC-92 Cleavage Fracture of Ship Plate as Influenced by Design and Metallurgical Factors NRC-93 Cleavage Fracture of Ship Plate as Influenced by Size Effects NRC-94 Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests NRC-96 Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests
NS-361	Consulting Services to Bureau of Ships on Division 18 Projects Project not established, but consulting services are being rendered
OD-25	X-Ray Investigation of Residual Stresses B-220 Residual Stresses in Cold-Drawn Non-Ferrous Alloys NRC-27 Prevention of Stress-Corrosion Cracking of Cartridge Brass by Protective Coatings, or Surface Treatment
OD-34-1	Determine the Relationships between Temperature and Times of Hold at Heat for Adequate Relief of Stress in Welded Structures (See OD-34-2)
OD-34-2	Evaluate Residual Stress in Welded Structures B-150 Report on Research Needs in Field of Welding and Summary of Existing Knowledge on Welding Practice NRC-3 Stress Relief of Weldments for Machining Stability NRC-17R Stress Relief of Welded Joints
OD-34-3	Develop a Steel Composition That Has Maximum Strength at or Near the Solidus and That, After Heat Treatment, Will Have Physical Properties Suitable for Gun Manufacture NRC-36 Metallographic and Physical Properties of New Types of Gun Steels NRC-38 Improvement in Wrought Gun Tubes NRC-39 Improvement in Gun Steel Ingot Practice NRC-50 Control of Basic Open Hearth Practice for Manufacture of Wrought Gun Tubes NRC-80 Prevention of Cracking in Gun Tubes NRC-81 Development of High-Strength Gun Steels NRC-85 Time-Temperature-Hardness Relations in New Gun Steels B-90 & B-160 Steel for Gun Tubes
OD-34-10	Determine the Fatigue Strength of Selected Gun Steels Under Various Combinations of Stresses B-189 Fatigue Strength of Selected Gun Steels
OD-35-1	Develop a Rapid Acceptance Test for Fire Clay Brick to be Used in Pouring Boxes for Handling Molten Steel Where the Brick Must Endure High Thermal Shock and Must be Strong Enough for Handling While Cold B-103 Acceptance Test for Fire Brick: Pouring Box Refractories

Army or Navy Control Number	Army or Navy Title and Division 18, NDRC Project Pertaining Thereto
OD-35-2	Develop a Suitable Substitute for the Sillimanite Wet Patch for Use as Seals in Connection with the Pouring of Molten Steels in Special Foundry Practice
	B-95 Development of a Substitute for Sillimanite in Pouring Rings Used in Special Steel Foundry Practice
OD-36-2	To Develop Precipitation Hardening Alloys That Can Be Utilized for Welding Electrodes. (Extended to include the development of electrodes for the repair welding of cast armor and for the welding of high-strength structural steels.)
	NRC-1 Weldability of Commercial Armor Plate
	NRC-2 Development of Ferritic Armor Welding Electrodes
	NRC-2R Development of Armor Welding Electrodes
	NRC-76 Development of Improved Electrode Coatings
	SP-28 Field Service in Welding of High Strength Structural Steels
	SP-29 Field Service in the Repair Welding of Cast Armor
OD-37-1	Determine the Factual Relationship Between Structure, Allotropy, Dilation Characteristics of Steels Used in Ordnance
	NRC-9 Evaluation of Weldability by Direct Welding Tests
	NRC-10 Evaluation of Weldability by Direct Measurement of Cooling Rates
	NRC-11 Evaluation of Weldability by Correlation of Electrical and Heat Constants
OD-38-2	Perfect a Method for the Rapid Determination of Oxygen, Hydrogen, and Nitrogen in Steel and for Coordinating the Effects of These Elements on the Structure and Physical Properties
	NRC-4 Effects of Hydrogen, Nitrogen, and Oxygen in Armor Plate
OD-74	Development of a Process for Manufacturing and Welding Face-Hardened Armor
	NRC-16R Welding Face Hardened Armor
	NRC-24 The Development of a Process for Manufacturing and Welding Face-Hardened Armor Plate
	NRC-29 Development of Processes for the Manufacturing and Welding of Homogeneous Armor Plate from Nonalloy Steels
	NRC-30 Development of Processes for the Manufacturing and Welding of Case-Carburized Armor Plate from Nonalloy Steels
OD-76	Direct Explosion Test for Welded Armor Plate
	NRC-25 Direct Explosion Test for Welded Armor and Ship Plate
OD-81	Study of Properties of Malleable Iron Castings for Use in Tanks, Combat Vehicles, and Other Military Applications
	NRC-28 Properties of Malleable Iron Castings for Use in Tanks, Combat Vehicles, and Other Military Applications
OD-82	Weldability of Commercial Armor Plate
	NRC-1 Weldability of Commercial Armor Plate
	NRC-59 Non-Metallic Welding Back-Up Strips for Armor Plate Joints
OD-83	Correlation of Metallographic Structures and Hardness Limit in Armor Plate
	NRC-5 Correlation of Metallographic Structures and Hardness Limit in Armor Plate
OD-84	Non-Ballistic Test for Armor Plate
	NRC-6 Non-Ballistic Test for Armor Plate
OD-85	Spot Welding of Armor Plate and Low-Alloy Steels
	NRC-12 Spot Welding of Armor Plate and Low-Alloy Steels
OD-86	Flash Welding of Alloy Steels for Ordnance and Non-Destructive Testing of Flash Welds
	NRC-13 Flash Welding of Alloy Steels for Ordnance
	NRC-57 Non-Destructive Testing of Flash Welds
OD-87	Improvement of Low-Alloy Armor Steels
	NRC-14 Improvement of Low-Alloy Armor Steels
	NRC-31 Investigation of Boron in Armor Plate
OD-88	Flame Hardening of Homogeneous Armor Plate
	NRC-23 Determination of the Effects of Flame Hardening on the Ballistic Properties of Pre-Heat-Treated Homogeneous Armor Plate
OD-106	Effect of Locked-up Stresses on Ballistic Performance of Welded Armor
	NRC-53 Effect of Locked-up Stresses on Ballistic Performance of Welded Armor
OD-107	Non-Alloy Steels for Armor-Piercing Capped Shot
	NRC-37 Investigation of the Use of Special Non-Alloy Steels for Armor-Piercing Capped Shot
OD-108	Centrifugal Casting Methods for Production of Miscellaneous War Matériel Items
	SP-10 Mathematics underlying the Centrifugal Casting of Metals (OD-108)
	NRC-26 Improvements in and Extension of Centrifugal Casting Methods for Production of Miscellaneous War Matériel Items
	NRC-33 Analysis of Heat Flow in Metal Molds for Centrifugal Casting of Gun Tubes, Airplane Cylinders, Tank Bogey Wheels and Other War Matériel
	NRC-34N Bibliography on Centrifugal Casting

Army or Navy Control Number	*Army or Navy Title and Division 18, NDRC Project Pertaining Thereto*
OD-113	Examination of Enemy Matériel NRC-32 Examination of Enemy Matériel
OD-114	Investigation of Acceptance Tests for Plain Carbon Steel Gun Forgings and Other Ordnance Forgings NRC-58 Acceptance Tests for Plain Carbon Steel Gun Forgings and Other Ordnance Forgings
OD-115	Heat Treatment of National Emergency Steels for Use in Tanks, Combat Cars, Gun Mounts, and Other Ordnance Matériel NRC-55 Heat Treatment of National Emergency Steels for Use in Tanks, Combat Cars, Gun Mounts, and Other Ordnance Matériel
OD-117	Study of Density and Volume Changes Associated with Phase Changes in Brass NRC-62 Study of Density-Volume Changes Associated with Phase Changes in Cartridge Brass
OD-123	Evaluation of Factors Affecting Crack Sensitivity of Welded Joints NRC-65 Evaluation of Factors Affecting Crack Sensitivity of Welded Joints
OD-136	Effect of Oxygen Cutting on Weldability of Armor Plate NRC-71 Effect of Oxygen Cutting on Weldability of Armor Plate
OD-144	Development and Extension of Precision Casting Methods for Production of Miscellaneous War Matériel Items NRC-69 Development and Extension of Precision Casting Methods for Production of Miscellaneous War Matériel Items
OD-156	Investigation of the Effect of Impurities on Ferro-Magnetism of Nonferrous Alloys NRC-79 Effects of Impurities on the Ferro-Magnetism of Nonferrous Alloys
OD-177	Manual on Effects of Shot Peening of Machine Parts and Laboratory Specimens Project not undertaken (see NA-115)
QMC-18	Development of a Suitable and Noncritical Coating for Steel in Cooking Utensils NRC-46 Development of a Suitable and Noncritical Fused Inorganic Coating for Cooking Utensils and Other Quartermaster's Items
QMC-21	Flatware for Army Use NRC-48 Flatware for Army Use SP-11 Silver Plating of Steel Flatware
QMC-25	Camouflage of Mess Gear NRC-54 Metallurgical Studies and Surveys of Army Quartermaster Corps Supplies
QMC-39	Corrosion-Resisting Alloy for Quartermaster Items NRC-91 Development and Evaluation of an Economical Corrosion-Resisting Alloy for Quartermaster Items
SOS-3	Possibilities of Interchangeable Use of the Materials and Alloys of the Platinum Group, Silver, Tungsten, and Others in Electrical Contacts SP-16 Rare Metal Contacts

Contract Number	*Contractor*	*Subject*
OEMsr-307	National Academy of Sciences	Metallurgical Advice to OSRD—NDRC
NDCrc-160	University of Michigan Ann Arbor, Michigan	Literature Survey on the Low-Temperature Properties of Metals
NDCrc-120 OEMsr-143	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Steel for Gun Tubes
NDCrc-181	Massachusetts Institute of Technology Cambridge, Massachusetts	Development of a Substitute for Sillimanite in Pouring Rings Used in Special Steel Foundry Practice
OEMsr-17	Ohio State University Research Foundation Columbus, Ohio	Acceptance Test for Fire Brick: Pouring Box Refractories
OEMsr-185 OEMsr-190	Massachusetts Institute of Technology Cambridge, Massachusetts	Development of Non-Magnetic Armor Steel
OEMsr-68	Ohio State University Research Foundation Columbus, Ohio	Research Needs in Field of Welding and Summary of Existing Knowledge on Welding Practice
OEMsr-152	University of Michigan Ann Arbor, Michigan	Fatigue Strength of Selected Gun Steels Under Combined Stress
OEMsr-208	Lehigh University Bethlehem, Pennsylvania	Residual Stresses in Cold-Drawn Non-Ferrous Alloys
OEMsr-552	Federal Shipbuilding and Dry Dock Company Kearny, New Jersey	Weldability of Commercial Armor Plate
OEMsr-535	Combustion Engineering Company New York, New York	Development of Ferritic Armor Welding Electrodes
Correlation project Company financed	Rustless Iron and Steel Corporation Baltimore, Maryland	Development of Armor Welding Electrodes
OEMsr-399	Ohio State University Columbus, Ohio	Stress Relief of Weldments for Machining Stability
OEMsr-449	Battelle Memorial Institute Columbus, Ohio	Effects of Hydrogen, Nitrogen and Oxygen in Armor Plate
OEMsr-448	Battelle Memorial Institute Columbus, Ohio	Correlation of Metallographic Structures and Hardness Limit in Armor Plate
OEMsr-417	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Non-Ballistic Test for Armor Plate
Symbol No. 923 Funds transferred	National Bureau of Standards Washington, D. C.	Beryllium-Aluminum Alloys for Engine Parts
OEMsr-478	American Brake Shoe Company Mahwah, New Jersey	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-447	Battelle Memorial Institute Columbus, Ohio	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-457	Climax Molybdenum Company Detroit, Michigan	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-462	Crane Company Chicago, Illinois	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-459	Federal Shipbuilding and Dry Dock Company (U. S. Steel Corporation) Kearny, New Jersey	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-509	Lunkenheimer Company Cincinnati, Ohio	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-508	Massachusetts Institute of Technology Cambridge, Massachusetts	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-505	The Midvale Company Philadelphia, Pennsylvania	Heat-Resisting Metals for Gas Turbine Parts
Symbol No. 934 Funds transferred	National Bureau of Standards Washington, D. C.	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-466	University of Michigan Ann Arbor, Michigan	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-527	Vanadium Corporation of America New York, New York	Heat-Resisting Metals for Gas Turbine Parts
OEMsr-445	Lehigh University Bethlehem, Pennsylvania	Evaluation of Weldability by Direct Welding Tests
OEMsr-396	Rensselaer Polytechnic Institute Troy, New York	Evaluation of Weldability by Direct Measurement of Cooling Rates
OEMsr-494	Columbia University New York, New York	Evaluation of Weldability by Correlation of Electrical and Heat Constants
OEMsr-391	Rensselaer Polytechnic Institute Troy, New York	Spot Welding of Armor Plate and Low-Alloy Steels

Contract Number	*Contractor*	*Subject*
OEMsr-451	Battelle Memorial Institute Columbus, Ohio	Flash Welding of Alloy Steels for Ordnance
OEMsr-450	Battelle Memorial Institute Columbus, Ohio	Improvement of Low-Alloy Armor Steels
OEMsr-492	John A. Roebling's Sons Company Trenton, New Jersey	Corrosion-Fatigue Failure of Aircraft Control Cables
Correlation project Rock Island financed	Rock Island Arsenal Rock Island, Illinois	Welding Face-Hardened Armor
Correlation project Rock Island financed	Rock Island Arsenal Rock Island, Illinois	Stress Relief of Welded Joints
OEMsr-647	University of California Berkeley, California	Properties and Heat Treatment of Magnesium Alloys
OEMsr-729	Battelle Memorial Institute Columbus, Ohio	Fatigue Properties of Magnesium Alloys and Structures
OEMsr-547	Massachusetts Institute of Technology Cambridge, Massachusetts	Determination of the Effects of Flame Hardening on the Ballistic Properties of Pre Heat-Treated Homogeneous Armor Plate
OEMsr-970	Buick Motors Division General Motors Corporation Flint, Michigan	The Development of a Process for Manufacturing and Welding Face-Hardened Armor Plate
OEMsr-712	Trojan Powder Company Allentown, Pennsylvania	Direct Explosion Test for Welded Armor and Ship Plate
OEMsr-650	U. S. Pipe and Foundry Company Burlington, New Jersey	Improvements in and Extension of Centrifugal Casting Methods for Production of Miscellaneous War Matériel Items
OEMsr-645	New Jersey Zinc Company Palmerton, Pennsylvania	Prevention of Stress-Corrosion Cracking of Cartridge Brass by Protective Coatings or Surface Treatment
OEMsr-730	Battelle Memorial Institute Columbus, Ohio	Properties of Malleable Iron Castings for Use in Tanks, Combat Vehicles and Other Military Applications
OEMsr-975	Buick Motor Division General Motors Corporation Flint, Michigan	Development of Processes for the Manufacturing and Welding of Homogeneous Armor Plate from Non-Alloy Steels
OEMsr-971	Buick Motor Division General Motors Corporation Flint, Michigan	Development of Processes for the Manufacturing and Welding of Case-Carburized Armor Plate from Non-Alloy Steels
OEMsr-721	Battelle Memorial Institute Columbus, Ohio	Investigation of Boron in Armor Plate
Symbol 1720A Funds transferred	National Bureau of Standards Washington, D. C.	Investigation of Boron in Armor Plate
OEMsr-722	Battelle Memorial Institute Columbus, Ohio	Examination of Enemy Matériel
OEMsr-731	Battelle Memorial Institute Columbus, Ohio	Analysis of Heat Flow in Metal Molds for Centrifugal Casting of Gun Tubes, Airplane Cylinders, Tank Bogey Wheels and Other War Matériel
Correlation project Naval research Laboratory financed	Naval Research Laboratory Washington, D. C.	Bibliography on Centrifugal Casting
Correlation project Company financed	American Brake Shoe Company Mahwah, New Jersey	High-Temperature Torch for Welding and Surfacing
OEMsr-724	University of Notre Dame Du Lac South Bend, Indiana	Metallographic and Physical Properties of New Types of Gun Steels
OEMsr-969	Buick Motor Division General Motors Corporation Flint, Michigan	Investigation of the Use of Special Non-Alloy Steels for Armor-Piercing Capped Shot
OEMsr-771	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Improvement in Wrought Gun Tubes
OEMsr-755	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Improvement in Gun Steel Ingot Practice
OEMsr-1123	Research Laboratories Division General Motors Corporation Detroit, Michigan	Effects of Shot Blasting on Mechanical Properties of Steel
OEMsr-840	Research Laboratory Westinghouse Electric and Manufacturing Company East Pittsburgh, Pennsylvania	Heat Treatment of High-Temperature Alloys

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OEMsr-822	Case School of Applied Science Cleveland, Ohio	Correlation of Information Available on the Fabrication of Aluminum Alloys
OEMsr-839	University of California Berkeley, California	Formability of Magnesium Alloy Sheet
OEMsr-819	Ferro Enamel Corporation Cleveland, Ohio	Development of a Suitable and Noncritical Fused Inorganic Coating for Cooking Utensils and Other Quartermaster's Items
OEMsr-902	Reed and Barton Corporation Taunton, Massachusetts	Flatware for Army Use
OEMsr-909	Timken Roller Bearing Company Canton, Ohio	Control of Basic Open-Hearth Melting Practice for Manufacture of Wrought Gun Tubes
OEMsr-894	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, I
OEMsr-864	Pennsylvania State College State College, Pennsylvania	Plastic Flow of Aluminum Aircraft Sheets Under Combined Loads, II
OEMsr-877	Massachusetts Institute of Technology Cambridge, Massachusetts	Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor
OEMsr-912	Massachusetts Institute of Technology Cambridge, Massachusetts	Metallurgical Studies and Surveys of Army Quartermaster Corps Supplies
OEMsr-1120	Research Laboratory Division General Motors Corporation Detroit, Michigan	Treatment of National Emergency Steels for Use in Tanks, Combat Cars, Gun Mounts and Other Ordnance Matériel
OEMsr-973	California Institute of Technology Pasadena, California	Radiographic and Fluoroscopic Methods of Inspection of Spot Welds in Aluminum Alloys
OEMsr-974	California Institute of Technology Pasadena, California	Non-Destructive Testing of Flash Welds
OEMsr-956	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Acceptance Tests for Plain Carbon Steel Gun Forgings and Other Ordnance Forgings
OEMsr-979	Battelle Memorial Institute Columbus, Ohio	Non-Metallic Welding Back-Up Strips for Armor Plate Joints
OEMsr-1048	General Electric Company Research Laboratory Schenectady, New York	Bi-Metallic Rotating Bands for Projectiles
Correlation project Company financed	American Brake Shoe Company Mahwah, New Jersey	Experimental Production of Pilot Static and Centrifugal Castings for the Armed Services
OEMsr-1084	University of Minnesota Minneapolis, Minnesota	Study of Density-Volume Changes Associated with Phase Changes in Cartridge Brass
OEMsr-1071	University of California Berkeley, California	Residual Stresses in Ship Welding
OEMsr-1030	Rensselaer Polytechnic Institute Troy, New York	Evaluation of Factors Affecting Crack Sensitivity of Welded Joints
OEMsr-1064	Lehigh University Bethlehem, Pennsylvania	Methods of Testing Weldability of Steel Plates and Shapes
OEMsr-1033	Rensselaer Polytechnic Institute Troy, New York	Physical and Stress-Corrosion Properties of Magnesium Alloy Sheet
OEMsr-1062	Rensselaer Polytechnic Institute Troy, New York	Spot Welding of Magnesium Alloys
OEMsr-1103	General Electric Company Schenectady, New York	Development and Extension of Precision Casting Methods for Production of Miscellaneous War Matériel Items
OEMsr-1083	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Deformation Characteristics of Magnesium Alloys
OEMsr-1187	Air Reduction Company New York, New York	Effect of Oxygen Cutting on Weldability of Armor Plate
OEMsr-1192	Massachusetts Institute of Technology Cambridge, Massachusetts	Investigation of Factors Reducing the Effective Ductility of Welded Steel Members
OEMsr-1217	University of California Berkeley, California	History of Residual Stresses in Welded Ships
OEMsr-1221	University of California Berkeley, California	Behavior of Steel Under Conditions of Multiaxial Stresses and Effect of Welding and Temperature on this Behavior
OEMsr-1270	Battelle Memorial Institute Columbus, Ohio	Development of Improved Electrode Coatings

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OEMsr-1247	Illinois Institute of Technology Chicago, Illinois	Behavior of Steel Under Conditions of Multiaxial Stress and the Effect of Metallographic Structure and Chemical Composition on this Behavior
OEMsr-1268	General Electric Company Schenectady, New York	Study of Effects of Surface Pre-Stressing on Dynamic Properties of Metals
OEMsr-1249	Lehigh University Bethlehem, Pennsylvania	Effects of Impurities on the Ferromagnetism of Non-ferrous Alloys
OEMsr-1265	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Prevention of Cracking in Gun Tubes
OEMsr-1286	Vanadium Corporation of America New York, New York	Development of High-Strength Gun Steels
OEMsr-348	California Institute of Technology Pasadena, California	Behavior of Metals Under Dynamic Conditions
Correlation project Company financed	American Brake Shoe Company Mahwah, New Jersey	Hardenability of Cast Steels for Use in Ordnance Matériel
Correlation project Company financed	American Brake Shoe Company Mahwah, New Jersey	Heat Resistant Alloys for Ordnance Matériel and Aircraft and Naval Engine Parts
OEMsr-1350	University of Pittsburgh Pittsburgh, Pennsylvania	Time-Temperature-Hardness Relations in New Gun Steels
OEMsr-1323	Lehigh University Bethlehem, Pennsylvania	Weldability of Steel for Hull Construction
OEMsr-1331	Battelle Memorial Institute Columbus, Ohio	Investigation of Metallurgical Quality of Steels Used for Hull Construction
OEMsr-1345	Battelle Memorial Institute Columbus, Ohio	Metal and Ceramic Materials for Jet Propulsion Devices
OEMsr-1382	Cornell University Ithaca, New York	Fatigue Tests of Ship Welds
OEMsr-1466	Rustless Iron and Steel Corporation Baltimore, Maryland	Weldability of Heat-Resisting Alloys
OEMsr-1400	Battelle Memorial Institute Columbus, Ohio	Development and Evaluation of an Economical Corrosion Resisting Alloy for Quartermaster Items
OEMsr-1418	University of California Berkeley, California	Cleavage Fracture of Ship Plate as Influenced by Design and Metallurgical Factors
OEMsr-1421	University of Illinois Urbana, Illinois	Cleavage Fracture of Ship Plate as Influenced by Size Effects
OEMsr-1426	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests
OEMsr-1471	Pennsylvania State College State College, Pennsylvania	Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests

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